Department of Ophthalmology
University of Helsinki
Helsinki, Finland

Preoperative visual acuity of cataract patients. Repeatability of visual acuity and refractive error measurements in clinical settings

Jaakko Leinonen

ACADEMIC DISSERTATION

To be publicly discussed,
by permission of the Medical Faculty of University of Helsinki,
in the Auditorium of the Department of Ophthalmology,
Haartmaninkatu 4, Helsinki,
on October 27th 2006, at 12 noon.

HELSINKI 2006

SUPERVISED BY:

Professor Leila Laatikainen
Department of Ophthalmology
Helsinki University Central Hospital

REVIEWED BY:

Docent Pentti Koskela
Department of Ophthalmology
Oulu University Central Hospital

Docent Olavi Pärssinen
Department of Ophthalmology
Turku University Central Hospital

ISBN 952-92-1068-X (nid.)
ISBN 952-10-3439-4 (PDF)

Yliopistopaino
Helsinki 2006

Contents

Abbreviations

BCVA	best corrected visual acuity
CR	coefficient of repeatability
DE	defocus equivalent
ECCE	extracapsular cataract extraction
ICCE	intracapsular cataract extraction
logMAR	logarithm of the minimum angle of resolution
REM	refractive error measurement
SDME	standard deviation of measurement error
SE	spherical equivalent
VA	visual acuity

List of original publications

This thesis is based on the following original publications, which are referred to in the text by their Roman numerals:

I Leinonen J, Laatikainen L: The decrease of visual acuity in cataract patients waiting for surgery. Acta Ophthalmol Scand 1999;77:681–684.

II Leinonen J, Laatikainen L: Changes in visual acuity of patients undergoing cataract surgery during the last two decades. Acta Ophthalmol Scand 2002;80:506–511.

III Leinonen J, Laakkonen E, Laatikainen L: Random measurement error in visual acuity measurement in clinical settings. Acta Ophthalmol Scand 2005;83:328–332.

IV Leinonen J, Laakkonen E, Laatikainen L: Repeatability (test-retest variability) of refractive error measurement in clinical settings. Acta Ophthalmol Scand 2006;84:532–536.

Abstract

The primary goals of the study were to investigate the degree and rapidity of vision loss in eyes awaiting cataract surgery and to estimate the proportion of expected lifespan that the waiting time for surgery comprised. Visual acuities at the time of referral and on the day before surgery were compared in 124 patients operated on for cataract in Vaasa Central Hospital, Finland. The expected survival of the patients after surgery was calculated individually using the Finnish life statistics.

During an average waiting time of 13 months, visual acuity in the study eye decreased from 0.68 logMAR to 0.96 logMAR (from 0.2 to 0.1 in Snellen decimal values). The average decrease in vision was 0.27 logMAR per year. In the fastest quartile, visual acuity change per year was 0.75 logMAR, and in the second fastest 0.29 logMAR, the third and fourth quartiles were virtually unaffected. The proportion of persons with visual acuity of 0.5 or better in the better eye decreased from 66% to 41%, and those with low vision (< 0.3 in the better eye) increased from 8% to 21%. The average worsening of the better eye during the waiting period was 0.14 logMAR.

The mean waiting time in relation to the expected survival for all 124 patients was 13%, varying from less than 5% in 10 patients to more than 25% in 8 patients.

Preoperative visual acuity and the occurrence of ocular and general disease were compared in samples of consecutive cataract extractions performed in 1982, 1985, 1990, 1995 and 2000 in two hospitals in the Vaasa region in Finland. From 1982 to 2000, the average preoperative visual acuity increased by 0.85 logMAR units (from 1.56 logMAR to 0.71 logMAR or 8.5 log lines corresponding to decimal values of 0.03 and 0.2, respectively. In the better eye, visual acuity increased from 0.64 logMAR to 0.37 logMAR, corresponding to decimal values of 0.23 and 0.43, respectively. The incidence of cataract surgery increased from 1.0 to 7.2 operations per 1000 inhabitants per year over this period. For an annual increase of one operation per 1000 inhabitants, the increase in average preoperative visual acuity was 1.3 log lines and in the better eye 0.4 log lines. The proportion of patients profoundly visually handicapped (VA in the better eye <0.1) before the operation fell from 15% to 4%, and that of patients less profoundly visually handicapped (VA in the better eye 0.1 to <0.3) from 47% to 15%.

The repeatability and standard deviation of random measurement error in visual acuity determination in a clinical environment in cataractous, pseudophakic and healthy eyes were estimated by re-examining visual acuity and refractive error of patients referred to cataract surgery or consultation by ophthalmic professionals. Altogether 99 eyes of 99 persons (41 cataractous, 36 pseudophakic and 22 healthy eyes) with a visual acuity range of Snellen 0.3 to 1.3 (0.52 to –0.11

logMAR) were examined. The healthy comparison group consisted of hospital staff. The mean time interval between the first and second examination was 45 days.

The repeatability estimated as a coefficient of repeatability for all 99 eyes was 0.18 logMAR, and the standard deviation of measurement error was 0.06 logMAR. Eyes with the lowest visual acuity (0.3–0.45) had the largest variability, standard deviation of measurement error 0.09 logMAR, and eyes with a visual acuity of 0.7 or better had the smallest, 0.04 logMAR. The coefficient of repeatability values was 0.24 logMAR and 0.12 logMAR, respectively. The variability may be partly explained by the line size progression in lower visual acuities, and partly by variability in measurement of the refractive error. The difference in the average visual acuity between occasions 1 and 2 (0.15 logMAR vs. 0.12 logMAR) was considered of interest because it indicates that some learning effect is possible.

The repeatability of refractive error measurement in a clinical environment was studied in the same patient material as the repeatability of visual acuity. Differences between measurements 1 and 2 were calculated as three-dimensional vector values and spherical equivalents and expressed by coefficients of repeatability. Coefficients of repeatability for all eyes for vertical, torsional and horisontal vectors were 0.74D, 0.34D and 0.93D, respectively, and for spherical equivalent for all eyes 0.74D. Eyes with lower visual acuity (0.3–0.45) had larger variability in vector and spherical equivalent values (1.14), but the difference between visual acuity groups was not statistically significant. The difference in the mean defocus equivalent between measurements 1 and 2 was, however, significantly greater in the lower visual acuity group. In all visual acuity groups, the mean difference vector was very close to the zero vector, which means that no systematic difference existed. Variability in refractive error measurement increased when visual acuity decreased. If a change of ±0.5D (measured in defocus equivalents) is accepted as a basis for change of spectacles for eyes with good vision, the basis for eyes in the visual acuity range of 0.3 – 0.65 would be ±1D.

Acknowledgements

This study was conducted at Vaasa Central Hospital during 1997–2006. I am indebted to the Head of the operative unit, Kaj Finne, for providing excellent working facilities.

My deepest gratitude is due to my supervisor, Professor Leila Laatikainen, for her guidance and constructive criticism and for consistently showing an interest in my work.

Docent Pentti Koskela, from the Department of Ophthalmology of Oulu University Central Hospital, and Docent Olavi Pärssinen, from the Department of Ophthalmology of Turku, University Central Hospital, are acknowledged for valuable advice in the preparation of this manuscript.

I also wish to express my gratitude to the following persons:

Eero Laakkonen, Lic Sc (Stat.), for performing the statistical analyses. I particularly thank him for multivariant statistics for vectors and discussions about variability in one- and three-dimensional measurements.

Carol Ann Pelli, Hon.B.Sc., for revising the English of this thesis.

The staff of The Ophthalmology Department of Vaasa Central Hospital for a positive attitude and generous help during this work

My son, Tomi Leinonen, M.Sc., for deepening my understanding of point spread function in the many discussions we had on this interesting subject.

Finally, I thank my family, and especially my wife, Marjukka, for taking an interest in this work and for gracefully bearing up under the pressure.

Financial support from the Finnish Eye Foundation is gratefully acknowledged.

1. Introduction

During the last 20 years, the number of cataract extractions has increased in relation to both the population and other ophthalmological operations (Jay & Devlin 1990; Stenevi et al. 1995; Norregaard et al. 1998a, 1998b, Lundström et al. 1999, 2001b, Taylor & Keeffe 2001). In Finland, cataract operations have increased from about 5000 in 1982 to approximately 41000 in 2003 (STAKES Reports 2005). Indications for cataract surgery, particularly visual acuity (VA) criteria, have therefore also changed. The factor with the greatest effect on the increase in cataract surgery is an improvement in surgical technique. Consequently, the waiting time for operations during the 1990s lengthened in many community hospitals in Finland to more than one year. One might expect that during this long waiting time the quality of life for patients who do not have many years of life left is decreased. This is especially true because mortality of cataract patients seems to be higher than the average for the population (Benson et al. 1988; Street & Javitt 1992).

Better visual results and improved quality of life, as measured by general life quality indicators, have increased the demand for earlier operations (Fletcher et al. 1998, Norregaard et al. 1998a, Oliver et al. 1998, Prajna et al. 1998, Jayamanne et al. 1999, Saw et al. 2002). Preoperative VA has improved (Cairns & Sommer 1984, Jay & Devlin 1990, Moorman et al. 1990, Obstbaum 1995, Norregaard et al. 1998a), and the number of second eye operations has increased, with second eyes being operated on earlier than before (Bernth-Petersen 1981, Castells et al. 2000). The increased incidence of cataract extraction has led to discussion about the optimal number of operations for the general population (Taylor 2000, Foster 2001) and for VA indications for extraction. According to a new law (856/2004), community hospitals in Finland must provide treatment within six months. The main indication for cataract operation is meeting the VA criterion.

It is well known that the development and progression rate of cataract are individual. Structural studies on increase in lens opacities by photographing opacities (LOCS II and III) have shown that nuclear opacities increase in five years in 46%, cortical opacities in 16% and posterior subcapsular opacities in 55% (Leske et al. 1996, 1997). Functional effects of cataract, e.g. VA change during cataract development, have not been widely investigated. A Finnish study (Rouhiainen et al. 1997) found a 0.07 logMAR worsening of VA in three years in early cataract eyes.

The most common examination performed for cataract and other ophthalmic patients is VA measurement, and many decisions are based on VA, but relatively few studies describe the reliability of VA measurement (Siderov & Tiu 1999). To define the best corrected VA, refractive error measurement (REM) is necessary. Reliability of REM has been evaluated mostly with healthy eyes (Goss & Grosvenor 1996). Many newer studies deal with the accuracy of autorefractors, the 95% confidence interval (inter- and intraexaminer) in spherical, cylinder and spherical equivalents being ± 0.5 diopters (Goss & Grosvenor 1996). The differences in refractive errors or differences in REM are presented in spherical equivalents, in spherical and cylindrical values separately or in vector matrices. The only accurate way to express these differences is to use mathematical model that takes into consideration the spherical component which is born of two obliquely crossed cylinders, and calculates the magnitude and direction of the new resultant cylinder (Harris 1990a). Several ways to calculate spherocylindrical differences are used (Cravy 1979, Harris 1990a, Naeser 1997, Thibos et al. 1997, Holladay et al. 1998).

This study evaluated the magnitude of VA change in patients awaiting cataract extraction and in those entering cataract surgery between 1982 and 2000. In addition, the repeatabilities of VA and REM of cataract and pseudophakic patients in clinical conditions were examined.

2. Review of the literature

2.1 Progression of cataract, morphological studies

Progression of nuclear, cortical and posterior subcapsular opacities has been investigated using LOCS II (Magno et al. 1993, The Italian-American Cataract Study Group 1994) and LOCS III (Leske et al. 1996, 1997) methods, but the corresponding VAs were not reported. Magno et al. (1993) found progression of one or more steps in LOCS II in 38% of patients for nuclear, 28% for cortical and 8% for posterior subcapsular cataract in six months (Table 13). The Italian-American Cataract Study (1994) found progression in 67%, 45% and 47% of nuclear, cortical and posterior subcapsular cataracts, respectively, over a three-year observation period for persons aged 65–74 years. Regression was also reported in 6%, 5.5% and 19% of nuclear, cortical and posterior subcapsular opacities, respectively, which according to investigators probably came from misclassifications. In the study of Leske and coworkers (1996), the progression rate for nuclear opacities was 36% after two years and after five years the follow-up progression rate for nuclear opacities was 46%, 16% for cortical and 55% for posterior subcapsular opacities (Leske et al. 1997). The incidence of cortical or posterior subcapsular cataract increased with age, but there was no significant difference in the progression rate of any opacity type in relation to age. McCarthy et al. (2003) followed a cohort of 2594 patients aged over 40 years (mean age 62.5 years) for five years. The overall progression of cataract was nuclear 19%, cortical 14% and posterior subcapsular 20%. The figures presented differ considerably, partly due to varying length of follow-up and partly due to different cataract classification systems and different definitions of change.

2.2 Increase in cataract surgery rate

The number of cataract procedures performed in the Western world has increased considerably during the last two decades (Jay & Devlin 1990, Stenevi et al. 1995, Norregaard et al. 1996, Lundström et al. 1999, 2001b, Taylor & Keeffe 2001). The increasing rate has been shown in relation to both the general population and other ophthalmic operations. People's willingness to undergo cataract surgery has increased because of improvements in the quality of vision and in the general quality of life after the operation (Desai et al. 1996, Espallargues & Alonso 1998, Oliver et al. 1998, Jayamanne et al. 1999, Monestam & Wachtmeister 2002). Patients undergo cataract surgery with better vision than before (Cairns & Sommer 1984, Jay & Devlin 1990, Moorman et al. 1990, Obstbaum 1995, Norregaard et al. 1998a, Monestam & Wachtmeister 2002). Early cataract extraction has been found to be beneficial also in very old patients (Bergman et al. 2004), increasing surgery rates among the elderly.

The Finnish National Research and Development Centre for Welfare and Health statistics (Stakes 2000) report cataract as the main diagnosis for 5335 hospital admissions in 1982. In 2000, the number of cataract operations was about 35000, and in 2003, about 41000 (Stakes 2005). Probably more operations were in fact carried out in 2000 since the statistics do not cover some private clinics. The figure of 2003 is more reliable because private clinics are also included. Extraction rates per 1000 inhabitants in Finland were 1.1 in 1982, 6.7 in 2000 and 7.8 in 2003. In Sweden, the rate of cataract surgery increased from 4.47 to 7.26 per 1000 inhabitants during 1992–2000 (Lundstrom et al. 2002). Over a six year period in the 1990s in Australia, cataract extraction rate increased from 6.0% to 7.7% (age-standardized rate), and the eye-specific increase was 43% (from 4.4% to 6.3%) (Tan et al. 2004).

2.3 Variability in clinical measurements

2.3.1 Variation in measurement results

Some inherent variability exists in biological and psychophysical measurement due to natural biological variation in the object being measured, and inaccuracy in the measurement itself. Because of measurement imprecision, variable results are obtained even if the biological state of the measured object is exactly the same (Bland 1988). Thus, most clinical measurements cannot be taken at face value; consideration must be given to their error.

2.3.2 Glossary

Repeatability of a method may be assessed by repeated measurements using a single method on a series of subjects (Bland 1988). Agreement of measurements can be obtained when measurements on the same subject are taken by two different methods and the results are compared. An estimate of limits of agreement is achieved by calculating $d - 2s$ (lower 95% limit) and $d + 2s$ (upper 95% limit), where d is the mean of differences between the results and s is the standard deviation of differences between results. The confidence limits for s can also be statistically calculated (Bland & Altman 1986). Reproducibility of the results of an experiment performed by a particular researcher are generally evaluated by other independent researchers by attempting to reproduce the original experiment to see whether their experiment yields similar results.

2.3.3 Repeatability of measurement

When two methods of measurement or two results by the same method are compared, neither provides an unequivocally correct result (Bland & Altman 1986). Therefore, the degree of agreement is assessed. It is most unlikely that repeated measurements on a group of subjects will always be exactly the same. A useful description of the dispersion of results is a plot of the differences between the two measurements against their mean (Bland & Altman 1986), known as Bland & Altman plot (MedCalc Manual 2005). The graph can also be used to check whether the variability or precision of a method is related to the size of the characteristic being measured (MedCalc Manual 2005). If for repeated measurements the same method is used, the mean difference should be zero. The measure of repeatability, the coefficient of repeatability (CR), can therefore be calculated as 1.96 (≈ 2) times the standard deviations of the differences between the two measurements (d2 and d1): $CR = 1.96 \times (\Sigma(d2-d1)^2/(n-1))^{0.5}$ (Bland & Altman 1986). The best estimate of the error standard deviation (s) is : $(\Sigma(d2-d1)^2/2n)^{0.5}$ (Bland 1988). The standard deviation of the differences between measurements obtained by two methods provides a good index of the comparability of the methods (Bland 1988). If we can estimate the mean and standard deviation reliably, with small standard errors, the difference between the methods can be said to be at most two standard deviations on either side of the mean, except with a small probability. How closely the differences follow normal distribution can be ascertained from a histogram (Bland 1988).

2.3.4 Studies investigating repeatability of visual acuity testing

Although VA measurement is perhaps the most common examination in ophthalmic practice, relatively few studies have dealt with the repeatability of VA measurement in clinical settings (Siderov & Tiu 1999). In controlled laboratory conditions, Arditi and Caganello (1993) found that VA may, with 95% confidence, be ascertained within ±0.1 log units in trained visually normal persons. Using Sloan letters, 5 letters per line and 0.1 logMAR line size progression in six different studies which were carried out with visually normal persons, the 95% confidence interval of repeatability varied between 0.08 logMAR and 0.12 logMAR (0.8–1.2 lines) (Raasch et al. 1998). Siderov and Tiu (1999) found that the 95% limits of agreement revealed ±0.15 logMAR repeatability for patients having acuities of at least 0.1 with various refractive errors and various clinical conditions. Rosser et al. (2001) examined cataractous, pseudophakic and early glaucoma eyes and found a Snellen acuity repeatability of ±0.24 logMAR (95% limits for agreement) when examined letter by letter and ±0.33 logMAR when expressed by lines. In these two studies, the Snellen visual acuities varied from 0.1 (6/60) to normal. An earlier study (Gibson & Sanderson 1980) on cataractous eyes (VA of 6/9 or worse) found a difference of 2 lines or more in 13% of cases. Studies on repeatability of VA testing using shorter examination protocols have recently been reported (McGraw et al. 2000, Camparini et al. 2001). These studies demonstrated that reducing the number of optotypes or faster reading of lines above threshold values did not essentially diminish the repeatability of VA testing. The recognizability of numbers, like that of letters, varies. However, the influence of the readability of letters has a minor influence on measurement error in acuity measurement (Raasch et al. 1998). Sloan letters yield slightly better acuities than British Standard letters (0.033 logMAR) (Raasch et al. 1998).

2.4 Comparison of dioptric powers

2.4.1 Spherical equivalent

Dioptric power to describe refractive error is presented as a three-dimensional power: spherical and cylindrical power and direction of cylinder axis. Mathematical handling of three dimensions is more complicated than comparison of only one dimension. The conversion to a one-dimensional power can be done by using spherical equivalent (SE), which is the spherical power plus half of the cylindrical power (with both their signs). A more appropriate name according to Harris (2000) is nearest equivalent sphere since SE, incorrectly, implies that spherical power exists that is equivalent to the spherocylindrical power. Because of its simplicity, SE is much used in clinical observance and research. The SE satisfies certain basic requirements and can, therefore, be used in statistical analyses to provide means, variances and so forth (Kaye & Harris 2002). An analysis done in SE alone loses, however, information about the other component of refractive power, the astigmatic component (Harris 2000, Kaye & Harris 2002).

2.4.2 Comparison of dioptric differences as three-dimensional power

In most cases, comparison of dioptric powers is equivalent to the situation of placing two obliquely (i.e. at an angle other than 90^{o}) crossing cylinders on each other in addition to their spherical powers. Besides bringing a new resultant cylinder in power and direction, this creates a new spherical power inherent in the combination of cylindrical powers. Clinical situations where two refractive powers are involved include comparing surgically induced refractive change, comparing of two refraction error measurement results, testing subjective refraction with cross-cylinder, over-refraction on spectacles, and estimating anisometropia between both eyes of a subject.

There are several methods for calculation of the power of two obliquely crossed cylinders (Harris 1990a, Naeser 1990, Holladay et al. 1992, Thibos et al. 1997, Naeser 1997). Each of these methods accomplishes the same task in a somewhat different way, using trigonometric identities which yield the same unique result for any single pair of obliquely crossed spherocylinders. The first to use matrix formalism was Long (1976), and the method was modified to a simpler formalism by Keating (1980). A standard system for analyzing and reporting refractive data so that comparisons of different variables can be made is according to Harris the dioptric power matrix (Harris 1990a,b,c, Harris 2000, Kaye & Harris 2002). The formulas used in vector transformations are shown in Table 1. For power expressed in spherocylindrical form as Fs (sphere), Fc (cylinder) and ax (axis, degrees), the component vectors of the dioptric power matrix are given by Long's equations, which were also used by Harris (Harris 1990a, 2000, Kaye & Harris 2002). Keating (1981) and Harris (1990a) called these vectors f11, f12 and f22. Long (1976) called vectors horizontal, torsional and vertical. Harris (2000) called f11 and f22 diagonal (ortho-astigmatism) vectors and f12 an off-diagonal (oblique astigmatism) vector. Each spherocylindrical refractive power can be expressed unequivocally by these three vectors.

Table 1. Calculation of the three vectors of spherocylindric refractive power *

f11 (vector in vertical meridian)	Fs + Fc $\sin^2$ax
f12 (torsional vector)	–Fc sinax cosax
f22 (vector in horizontal meridian)	Fs + Fc $\cos^2$ax

* Fs spherical power (D), Fc cylindrical power (D), ax cylinder axis (degree)

Vectors f11, f12 and f22 can be returned to conventional spherocylindric form by Keating's procedure (Keating 1980, Harris 1990a). The mean value of several spherocylindrical values is obtained by averaging each vector column in a matrix separately. The mean value is the vector value of each column (Harris 1990a). This, again, can be converted back to conventional form by Keating's procedure.

Meaningful statistical inference of refractive values dispersion cannot be performed with the sphere, cylinder and axis (Harris 1990a). The description of the dispersion of a sample of dioptric (vector) values has to be done by multivariate mathematics. The complete variance-covariance matrix represents the dispersion of values fully and opens the way for the formal statistical analysis of measurements of dioptric power (Harris 1990a).

2.4.3 Studies testing repeatability of refractive error measurement (REM)

The standard method of refraction is conventional subjective refraction, and so far, no other refraction methods have replaced it in validity and practicality (Goss & Grosvenor 1996). Other methods, such as retinoscopy and the use of autorefractors, can serve as a starting point for subjective refraction.

Like measurement of VA, refractive error measurement (REM) is a psychophysical examination that has a tendency to vary as a result of several factors. The ability of different persons to discern dioptric differences ranges from 0.12D to 1.0D (Borish & Benjamin 1998). Differences in forced choice, pupil size, and ocular and general health can affect REM results (Borish & Benjamin 1998). Changes in fixation state of accommodation can also influence refraction (Elliott et al. 1997). Rubin and Harris (1995) reported that an autorefractor gave very stable results with an artificial test eye in rapid successive measurements, but similar measurements in healthy human eyes yielded more variable results. This variation was thought to be basicly due to two or more different fixation points or to reflect accommodative or other anomalies. Corneal refraction has been found to change under different blinking conditions; when blinking interval increases, corneal aberrations increase as a consequence of tear film changes (Montes-Mico et al. 2004). Tolerance to defocus increases when visual acuity decreases (Legge et al. 1987). As a result, precision of REM is also likely to decrease.

Investigations measuring repeatability of subjective REM are rare, and most of these have been conducted on healthy eyes. Zadnik et al. (1992) reported subjective refraction repeatability of sphere to be –0.063 ±0.63D (95% CI). Goss & Grosvenor (1996) reviewed papers that had studied repeatability of conventional and autorefraction; in most of these the intraexaminer and interexaminer reliabilities of subjective refraction were close to 80% agreement within ±0.25D and 95% agreement within ±0.5D for spherical equivalent, sphere power and cylinder power. Similarly, Johnson et al. (1996) found that repeatability in eyes with 0.5D or more cylinder power in 40 persons aged 18 to 40 years with three subjective astigmatism tests was ±0.25D in 88% and ±0.5D in 93%. In contrast, Rosenfeld and Chiu (1995) reported better repeatability of subjective refraction in vision professionals (12 teachers or students of optometry): ±0.27D for sphere, ±0.16D for cylinder and ±17.1° for axis as 95% limits of agreement. All of these studies were made without vector calculations.

Many studies describe variation of refractive values separately in spherical and cylindrical powers, which leads to inaccuracies because of the three-dimensional nature of refractive power (Harris 1990a, McKendrick & Brennan 1995, Rubin & Harris 1995, Elliott et al. 1997, Kaye & Harris 2002). Studies investigating repeatability of subjective REM are relatively scarce (McKendrick & Brennan 1995, Rosenfeld & Chiu 1995, Goss & Grosvenor 1996, Johnson et al. 1996), and most investigations have been performed on healthy eyes of reasonably young persons. The intervals between initial refraction and re-refraction and the methods used in calculations vary. Studies describing variability of REM in clinical settings and in eyes with ocular diseases are even fewer. It is, however, possible that some difference exists between repeatability of REM in healthy eyes and in eyes with decreased VA.

Elliott et al. (1997) used vector calculations in measuring repeatability of subjective refraction when they compared repeatability of two automatic refractors (Nikon NRK-8000 and Nidek AR-1000) and subjective refraction in healthy eyes with VA of 6/6 or better. They defined coefficient of repeatability as vertical (V), torsional (T) and horizontal (H) variability. Repeatability of subjective refraction (95% CI) was 0.611D (V), 0.224D (T) and 0.490D (H). The torsional component was equivalent to 1D cylinder axis variability of ±9.2°. A larger variability in subjective refraction was described by McKendrick & Brennan (1995) who found 2.21D for horizontal, 0.56D for torsional and 2.02D for vertical components. The subjects (n=20) were students of optometry evaluated by more than one tester.

2.5 Defocus equivalent

Refractive error causes blur, which worsens VA. Empirical studies express the dependence of VA on refractive error. The statistics of these studies (Table 2) give VA values for normal eyes having a best corrected visual acuity (BCVA) of 1.0 or better. In eyes with astigmatism, the spherical equivalent does not provide sufficient information to predict its effect on VA (Holladay et al. 1991). For instance a patient with a refraction of sf –1 cyl +2 ax 90° has a spherical equivalent of zero, but certainly does not have the same VA as a person with zero refractive error. To eliminate this inequity, a value termed the defocus equivalent is calculated that is proportional to the area of blur circle formed on the retina by various spherocylindric refractive errors (Holladay et al. 1991). The blur circle correlates to Snellen VA in an eye in which accommodation is inhibited. The defocus equivalent is equal to the sum of the absolute value of the spherical equivalent and half the absolute value of the cylinder (Holladay et al. 1991). Thus, a refractive error of sf –1 cyl +2 ax 90° yields a defocus equivalent of 1D.

2.6 Visual acuity

2.6.1 Definition of visual acuity

Visual acuity (VA) is the spatial resolving capacity of the visual system. The limits to VA are imposed by optical and neural factors or their combination. The minimum separable resolution is the least separation between two adjacent points that allows the two to be seen as separate (Bailey 1998). In the human eye, this is about one minute of arc, which is equivalent to 1.75 mm separation of two points at a distance of 6m. The European notation for one minute of arc acuity is the decimal value 1.0. The Anglo-Saxon notation is 6/6 or 20/20. The values are inversed values to resolution angle. A greater value expresses better VA. Thus, a person whose resolution at 6 m is 1.25 mm is assigned VA value of 1.4 (6/4.3 or 6/4 ; 20/14) and a resolution of 14 mm 0.125 (6/48; 20/160).

2.6.2 LogMAR

Logarithmic scaling of size on VA charts has long been advocated (Westheimer 1979, Bailey 1998) and is now broadly accepted. Westheimer (1979) provided evidence and argument that logarithmic scaling is more appropriate than other alternatives. Logarithmic scaling is in accordance to Weber-Fechner law, which states that the relationship between stimulus and perception is logarithmic. LogMAR is defined as $\log_{10}$ of the Minimum Angle of Resolution. Thus, a Snellen VA of 1.0 is 0 logMAR and Snellen VA 0.1 is 1.0 logMAR (with VA 0.1 the resolution is 1/0.1 = 10 minutes of arc, the logarithm of which is 1.0). LogMAR value can also be obtained directly by taking the logarithm of the VA decimal value and changing the sign. Bailey-Lovie letter chart (Bailey 1998) or ETDRS chart have 0.1 logMAR rating and ten lines between VA values 1.0 and 0.1. The lines are in constant size proportion with each other, $10^{0,1} \approx 1.26$ or each line is 26% greater than the line below it. 0.1 LogMAR represents one line in the ETDRS chart. Thus, 0.1 logMAR can be expressed as a log line which has a definite relative magnitude with regard to the ETDRS chart. A VA change of 0.3 logMAR to 0.7 logMAR has the equivalent of 4 log lines. Like logMAR, expression log line can also be widened over the range of 0 to 1.0 of the ETDRS chart.

2.6.3 Normal visual acuity

The traditional 1.0 is a limit at the poorer end of the normal range. Most normally sighted persons have acuity that is measurably better than 1.0 (Bailey 1998). Elliott et al. (1995) found that the average VA was better than 1.25 (6/4.8). In addition, 58-year-old persons with healthy eyes had VA of –0.1 logMAR (VA 1.25) and 77-year-old persons had VA of –0.02 logMAR (VA 1.05) (Elliott et al. 1995, Bailey 1998). Population studies where diseased eyes are included show lower values (Westheimer 2003). Sixty-year-old persons showed median VA of 1.0, 70-year-olds about 0.8 and 80-year-olds 0.5. Increasing age is associated with increased intraocular scatter of light (Westheimer 2003). This becomes a problem when trying to detect a small dim feature or when resolving dark letters against a bright backround (Ijspeert et al. 1990, Westheimer & Liang 1995). Sjöstrand et al. (2004) found an accelerating decline in eyes without any clinical signs of disease; between 30 and 69 years, the decline was 0.03 logMAR/10 years and after 70 years 0.09 logMAR.

2.6.4 Measurement of visual acuity

In clinical settings, the standard testing distance is 5 or 6 m, which provides slight accommodation. Because many examination rooms are too short to allow a 6-m viewing distance, mirrors are used for both projector and observation paths. VA is measured separately for the right and left eyes, and binocular VA can also be included. For clinical decisions, the best refractive correction is mostly used, giving the best corrected visual acuity (BCVA). VA without correcting lenses (uncorrected VA) is needed when evaluating the need for eye glasses, professional qualification, driver's license or refractive surgery. Habitual VA is VA with own spectacles. Pinhole acuity is VA with a pinhole aperture, usually 1.0–1.5mm in diameter (Bailey 1998).

Most VA tests use high-contrast black-on-white optotypes. With printed charts, it is common to have dark-to-light luminance ratios of 3:100 or 5:100. Projector contrast values are usually lower, between 10 : 100 and 20 : 100 (Bailey 1998).

Testing is usually performed with subdued illumination. Recommendations for a standardized chart luminance range from 85 to 300 cd/m^2. In this range, doubling the luminance changes VA score by about 0.02 logMAR (one fifth of a line). A typical compromise of chart luminance is 160 cd/m^2 (Bailey 1998), but because it is difficult to achieve this specific luminance a clinical tolerance of 80 to 320 cd/m^2 for test charts is reasonable (Bailey 1998). VA examination is usually performed in a moderate photopic adaptive range (Bailey 1998). High contrast VA is fairly constant over a wide luminance range; when log retinal illuminance range (trolands) varied between 2 and 5 units (illuminance variation 1000-fold), range log VA only varied between about 0.3 and 0.5 (VA variation only about 0.2 logMAR) (Westheimer 2003, Shlaer 1937).

2.6.5 Assigning visual acuity scores

The most common practice is to assign a VA score on a row-by-row basis (Bailey 1998). The VA score records the smallest size at which a set a specific proportion (typically 50%, but up to 80%) of all letters of that size are correctly identified. Row-by-row scoring is quite rough and VA score must change by at least two size levels in order for a clinician to be confident that there has been a significant change (Bailey 1998). Despite its relative insensitivity, the row-by-row method remains the most widely used by clinicians (Bailey 1998). Many clinicians give partial credit by recording plus or minus signs to indicate that a patient actually did a little better or worse than the reported numerical value. The ETDRS table has five letters on each row. Each row has a value of 0.1 logMAR. Thus, each letter has a value of 0.02 logMAR. The total number of correctly read letters gives the logMAR score.

2.6.6 Influence of scoring on visual acuity results

The VA score can be assigned by the line method, letter-by-letter analysis or probit analysis. Vanden Bosch & Wall (1997) compared the influence of these scoring methods on VA repeatability using EDTRS charts. Line assignment referred to the last line where three of the five letters are correctly read. Probit analysis referred to 50% seeing threshold frequency which was analysed in their study by computer software. The study was conducted on normal subjects (n=38) and patients with macular disease (n=32). The standard deviation (SD) of repeated measurements was greatest on line assignment 0.049 logMAR for both healthy and diseased eyes. For the letter-by-letter method, the SD was 0.034 for healthy eyes and 0.038 for diseased eyes. The results of probit method were similar to those of the letter-by-letter method.

VA is measured by clinicians most often on a chart having lines from 0.05 to 1.6. Theoretically, a VA value 0.4 means that the patient has an acuity of 0.4 or over but less than 0.5. The exact value is anything from 0.4 to 0.499. When doing comparisons between two or more values, this inaccuracy decreases because the same inaccuracy is repeated in all measurements. This could have meaning when the absolute value of VA is estimated.

Raasch et al. (1998) showed in their empirical study of 19 normally sighted volunteers from the student population that the inaccuracy of VA determination increases when the size progression between lines increases. As the size progression between lines increased by the factor n, the standard deviation of the VA score increased by the factor $\sqrt{n}$. In their study, VA score was not dependent on the number of letters at each size level (from one to ten letters per line).

2.6.7 Other factors affecting visual acuity measurement results

Psychological factors: Seeing involves discrimination not only of detail, size and position, but also shape and pattern texture. All this is in the context of meaning, expectations and past experience, modified by other senses, and varying with general health, fatigue, boredom, drugs or emotional state (Michaels 1975a).

Crowding phenomenon: An amblyopic eye does considerably better when letters are presented individually than when crowded together. This is also true with other eyes having any decrease in resolution (Michaels 1975a).

Binocular summation: Normal binocular vision improves functional vision by binocular summation and stereopsis as compared with monocular viewing. This increase is small in sensitivity when measured by threshold responses (Harwerth & Schor 2003).

Exposure duration: In most observers, VA is worse in the range of 0.1 to 0.5 second exposure duration than compared with longer exposures (Westheimer 2003).

Meridional variations in acuity: The usual finding is that horizontal and vertical meridians are favoured, although this is not universally so. The differences rarely exceed 15%, or 0.06 logMAR (Westheimer 2003).

Spurious resolution: When resolution of three lines (e.g. E-optotype) is measured and the size is decreased to under the minimum resolvable, the detection of correct direction might happen because two of three lines are seen on each other and the line between is not seen (Bennett & Rabbets 1984a)

Binocular VA is known to be 5% to 10% better than monocular VA, even with rough clinical measurements (Michaels 1975a). This is probably true because of Fechner's paradox: the seeing eye is inhibited by covering the other eye (Michaels 1975a).

2.6.8 Refractive state and visual acuity

Approximate VA values depending on spherical and cylindrical error found in the literature are summarized in Table 2. In a review article, Smith (1991) gave a formula showing the dependence between refractive state and VA as follows: A (minimum angle of resolution) = $(1 + (kDE)^2)^{0.5}$. This formula refers to spherical refraction errors and is designed for small refractive errors. The formula takes into account the pupil size D (mm), the refractive error E (diopters) and an empirical factor k, which has in various studies been assigned values between 0.55 and 1.33 (Smith 1991). The values in Table 2 (column 4) are calculated with a 3-mm pupil and a k-value of 0.85. When E is large, the factor kDE >> 1 and the formula approaches asymptotically a simpler form A = kDE indicating that defocus blur is directly proportional to refractive error.

Table 2. Visual acuity (VA) depending on refractive error. A literature review

Spherical error (D), Snellen VA				Cylindrical error (D), Snellen VA	
Error (D)	Bailey (1998)	Westheimer (2003)	Smith (1991) *	Cyl error (D)	Bailey (1998)
0.0	1.2	1.0	1.0	0.25	1.2
0.25	1.0	0.85	0.85	0.50	1.0
0.5	0.67	0.67	0.63	1.0	0.5
1.0	0.33	0.33	0.37	1.5	0.33
1.25	0.25	0.28	0.31	2	0.25
2.5	0.1	0.1	0.16	3	0.1

* pupil 3 mm, k 0.85

2.7 Limitations of the optical quality of the eye

Imagery, even of the healthy eye, like other optical instruments, is imperfect. The image of a point source is not a point in the retina, but a wider area, the central part of which is more illuminated and called the Airy disc (Westheimer 2003). The actual light spread of a point is called point spread function (Westheimer 2003). It is difficult to ascertain the value for the light distribution in the retinal image, but indirect measurements have shown that it has a form resembling the normal curve (Westheimer 2003).

Once the basic information of a point source is available, it is possible to describe the light distribution in any object merely by superposing the spread functions centred on all elements making up the object (Westheimer 2003).

2.7.1 Factors contributing to point spread

2.7.1.1 Diffraction

According to the wave theory of light, limitation of the aperture causes a spread of light even in a fully focused system. The Fraunhofer diffraction image of a point object has a bell shape with oscillating fringes. It comes to first zero at a radial distance of 1.22 λ/a, where λ is the wave length and a is the pupil diameter. The height of the first ring is only 1.75% of the height of the central peak (Airy disc) (Westheimer 2003). When pupil diameter is less than 2 mm, the actual image spread is equal to the diffraction image.

2.7.2 Aberrations

2.7.2.1 Chromatic aberration

For pupil diameters greater than 5 mm, the spread of point source in the retina is usually increased because the peripheral regions of the cornea and lens are afflicted with optical aberrations.

The optical components of the eye (cornea and lens) produce chromatic aberration. The total chromatic aberration of the photopic human eye is about 3 D(Glasser & Kaufman 2003). The chromatic aberration is greatest for red and blue. Red and blue fringes around an object are less likely to be seen as a result of the cones' relative insensitivity at the ends of the spectrum. Also, the visual processing in the retina and brain can sharpen the edges of the retinal image (Glasser & Kaufman 2003). The lens of a typical 20-year-old absorbs about 30% of incident blue light. At the age of 60, a typical lens absorbs 60% of incident blue light. This decreases both chromatic aberration and subtle colour discrimination (Glasser & Kaufman 2003). If refractive error is adjusted to zero at a wavelength of 588 nm, refraction at 530 nm is –0.4 D and at 650 nm about +0.3 D (Bennett & Rabbetts 1984b).

2.7.2.2 Spherical aberration

The peripheral parallel rays entering the cornea and the lens bend more than central rays; this is known as spherical aberration. The total spherical aberration of the human eye varies from 0.25 to 2.0 D (Miller 2003). Experimental studies show that the amount of spherical aberration is generally less than 1.0 D (Ciuffreda 1998). The optimal focus under dim conditions (e.g. night driving) might be increased up to 0.50 D myopia (Bennett & Rabbetts 1984b).

2.7.2.3 Other aberrations

The total amount of optical aberrations in the eye is much greater. These aberrations are caused mainly by cornea or lens or irregularities or irregularities in other ocular structures and can be demonstrated by wave front analysis and described by for example Zernike polynomials (Hamam 2003).

2.7.3 Other factors

2.7.3.1 Ocular media and accommodation as factors contributing to point spread

Scatter: Because the ocular media have some microscopic and ultramicroscopic structures, light is scattered in its passage from the cornea to the retina (Westheimer 1995, 2003). This phenomenon increases with age. Absorption: The media are not uniformly transparent to incoming light. Shorter wavelengths are absorbed more. Focus factors: The accommodative stance is not necessarily appropriate to the stimulus distance. This is especially possible when no sharply delineated targets are available.

2.8 Retinal factors

Retinal anatomy: In the fovea, the cones are packed approximately two to a linear minute of arc. Therefore, in principle, it is impossible to resolve patterns that are separated by less than half a minute of arc. Stiles-Crawford effect: Parallel rays of light entering the pupil through its center are more effective in stimulating retinal cones than those that enter near the edge of dilated pupil, reaching retinal cones somewhat more obliquely. This phenomenon reduces the effect of optical aberrations (Ciuffreda 1998).

2.9 Minimum resolution (visual acuity)

The resolving power of the eye in the simplest situation is when two points are moved apart until the observer can perceive them as separate. Each of the two points would be imaged on the retina with the light distribution of a point spread function. Resolution can be achieved when the peak/trough ratio is sufficiently great that the points can be seen as separate (Westheimer 2003). This ratio, often called Rayleigh criterion, states that resolution is obtained when separation of two Airy discs is at least half of the two peaks. The depression or saddle between the peaks then has a minimum illumination of 74% of that of the peaks. For a 3-mm pupil and a wavelength of 555 nm, the value is 47 seconds of arc (Bennett & Rabbetts 1984a).

2.10 Refractive error and its measurement

2.10.1 Main categories of recractive errors

Emmetropia is the static ocular condition in which refractive power is proportional to axial length (Michaels 1975b). Bennett & Rabbetts (1984c) define emmetropia in a similar way: an unaccommodated eye which brings parallel pencils of rays from a distant object to a sharp focus on the retina. In ametropia this is not true. Ametropias can be divided into two main categories (Bennett & Rabbetts 1984c): spherical ametropia and astigmatism. Anatomically, there is disproportion between the eye's length and optical power. The myopic eye can be regarded as having an optical system too powerful for its axial length, and a sharp image is formed in front of the retina. To focus on the retina, the object must be closer than an infinite distance from the eye (the point conjugate with the fovea, far point = punctum remotum) (Bennett & Rabbetts 1984c). If the rays within the eye are intercepted by the retina before reaching their focus, the resulting error of refraction is called hyper(metr)opia.

In axial ametropia, the eye is assumed to have a ”standard” power of +60 D so that any refractive error can be attributed to an ”error” in standard length. In "refractive" ametropia, the axial length of a reduced eye is assumed to have a standard value of 22.2 mm, with any defect attributed to an "error" in the power (Bennett & Rabbetts 1984c). Most human eyes show at least a slight degree of astigmatism. There are two contributory factors. The cornea is seldom truly spherical, even in the vicinity of the eye's optical axis. The second possible source of ocular astigmatism is the crystalline lens (Bennett & Rabbetts 1984d), or irregular shape of the cornea or the lens.

In general, any astigmatic surface can be regarded as combining an element of spherical power with an element of cylindrical power. In the standard notation (Tabo), a meridian is specified by the anti-clockwise angle it makes with the horizontal. An astigmatic lens has no sharp focus. In the steepest meridian, the focus closest to the refracting surface forms the first focal line, which is perpendicular to the steepest meridian. The weakest refracting surface of an astigmatic lens is perpendicular to the steepest meridian and focuses a line behind the first focus (the second focal line). These lines are perpendicular to each other, and the distance between them is called the Sturm's interval (Michaels 1975c). Representative cross-sections of Sturm's conoid are mostly elliptic, and the circle of least confusion is situated in Sturm's interval.

Power in oblique meridians: Since a cylinder has meridians of maximum and minimum curvature (power), intermediate curvatures must also exist. The intersection of an oblique plane with a solid cylinder forms an ellipse. If an assumption is made that an incident beam is paraxial, which concerning the eye is reasonable, the oblique curvature is related to the maximum curvature by $R_\theta = R \sin^2 \theta$, where R is the maximum curvature and θ the meridian (degrees) from the axis (Michaels 1975c). For example; if we have a cylinder 1D axis 0, power in the meridian 90° (from the axis) is 1D, in the meridian 70° from the axis 0.88 D, and in the meridian 30° from the axis 0.25 D.

2.10.2 Astigmatism and visual acuity

The dimensions of the focal lines and the circle of least confusion of an astigmatic pencil are directly proportional to the amount of astigmatism in diopters. This has a direct bearing on unaided vision. Since vertical and horizontal lines predominate in test letters as well as in most of the objects in our environment, vision is poorest when astigmatism is at an oblique axis (Bennett & Rabbetts 1984d).

2.10.3 Distance-correcting lens

Corresponding to both of the principal meridians, the correcting lens must be astigmatic, its principal meridians aligned with those of the eye and its principal powers such that the second principal focus (in the retina) coincides in each case with the eye's far point (Bennett & Rabbetts 1984d).

2.11 Measurement of refractive error

2.11.1 Methods of measurement

Refractive error can be measured objectively by retinoscopy (skiascopy) or automatic refractor, or subjectively. Nowadays, often all of these three methods are used by the clinician for each patient. Although automatic refractors have improved in quality, it is most likely that retinoscopy will be the essential part of refraction error measurement (Campbell et al. 1998). Beside being fast and accurate in an expert's hands, it gives valuable information to a clinician about ocular media and refractive irregularities.

For subjective refraction, the accepted rule is that the highest positive or lowest negative power that gives the best acuity is regarded as the ametropic error (Bennett & Rabbetts 1984e, Michaels 1975d). It does not necessarily follow, however, that this is the lens that will be prescribed. Entering into the final decision are the patient's symptoms, habits, requirements, previous prescription and the binocular cooperation of the eyes (Michaels 1975d). The final monocular spherical end point is reached by unfogging a fogged eye by 0.25 D steps until maximum VA is reached (Borish & Benjamin 1998). This also can be done by the Duochrome method on a red/green chart by 0.25 D steps (Borish & Benjamin 1998). Most often, the first green is the appropriate end point in young accommodating persons. Bennett and Rabbetts (1984e) suggested that presbyopes be left slightly in the red to preserve accommodation.

2.11.2 Tolerance to refractive errors

Legge et al. (1987) investigated modulation transfer with healthy eyes and eyes with low vision at medium and low spatial frequencies. With dilated pupils, depth of focus increased from 2.5 D in 3.5 c/deg to 17 D in 0.25 c/deg. They came to the conclusion that tolerance to defocus increases with low spatial frequences and found the same result in 30 eyes with low vision.

2.12 Effects of cataract on visual acuity and refraction

2.12.1 Lens transparency

Transparency of the lens depends on minimizing light scattering and absorption. Light passes smoothly through the lens as a result of the regular structure of the lens fibres, the absence of membrane-bound organelles, and the small and uniform extracellular space between the fibre cells. Cataract is any opacification of the lens, and it is clinically significant when opacification interferes with visual function (Beebe 2003). Loss of lens transparency can arise from an increase in light scattering or light absorption, which may be caused by disruption of the structure of lens cell fibres, increases in protein aggregation, phase separation in the lens cell cytoplasm or a combination of these (Beebe 2003).

2.12.2 Loss of vision due to cataract, longitudinal studies

There are fairly few studies describing longitudinal change in VA in cataractous eyes. In a Finnish epidemiological study, Rouhiainen and coworkers (1997) found an average decrease of 0.07 logMAR units in corrected VA in three years in eyes in which progression of early lens opacity was verified by the LOCS II method. Desai et al. (1999) recorded the profiles of 18 454 patients aged 50 years or older at entry to the waiting list for cataract surgery and at the time of surgery. At entry to the waiting list, 31% had VA 6/12 or better, 54% between 6/18 and 6/60 and 15% less than 6/60. At the time of surgery, of patients with VA 6/12 or better, the vision had deteriorated to 6/18–6/60 in 33% and in a further 3% to below 6/60. Of the group with VA <6/12–6/60, 13% had less than 6/60 vision by the time of surgery. Richter-Mueksch et al. (2001) examined patients with delayed presentation for cataract surgery. They found a significant difference in both preoperative VA between women and men (mean VAs of 0.31 and 0.24, respectively) and duration of preoperative visual deterioration (8.6 months for women and 12.2 months for men).

2.12.3 Change of refraction in cataract patients

The myopic shift of eyes with nuclear cataract is well known. Pesudovs and Elliott (2003) demonstrated that eyes with cortical cataract had greater astigmatic shift than control eyes with clear lenses. The follow-up time was one year and the astigmatic change in eyes with cortical cataract was 0.71D (SD±0.67), as compared with 0.24D (SD±0.20) in control eyes. This was probably because of the localized refractive index changes along cortical spoke opacities within the pupillary area. The nuclear cataract group showed a significant myopic shift of –0.38D (SD±0.60) compared with +0.02D (SD±0.21) in the control group). In The Blue Mountains Eye Study (Guzowski et al. 2003), there was a hyperopic change in the younger patient group (+0.41D, in persons aged 49–54 years) and a myopic shift in older patients (–0.22D in persons aged 75 years or older).

2.13 Effect of cataract on contrast and glare sensitivity

Small letter contrast sensitivity has been shown to be a more sensitive measure of early cataract than VA and large letter contrast sensitivity (Elliot & Situ 1998). However, its usefulness may be limited by its strong correlation with VA (r^2=0.70). By using cataract simulation with an angular distribution of light scatter similar to real cataract on clinical vision (VA, contrast sensitivity and glare) and real world vision (face recognition, reading speed and mobility orientation), Elliott et al. (1996) demonstrated that the effect of cataract simulation on VA was quite small, but it was much larger on contrast sensitivity and low contrast acuity with and without glare. Elliott et al. (1989) found that contrast sensitivity decline with cataract is an intermediate and high frequency loss. For nuclear and cortical cataracts with VA Snellen >0.3 (<0.5 logMAR), there was no loss of contrast sensitivity at the lowest spatial frequency (1 c/deg). For posterior subcapsular cataracts, low spatial frequency contrast sensitivity loss did occur, but was unrelated toVA. Glare sensitivity increased for all cataract types. This was related to VA for both cortical and nuclear cataracts, but not for the posterior subcapsular type. Their conclusion was that contrast and glare sensitivity measurements are a useful part of assessment of visual function in patients with posterior subcapsular cataract.

Neumann et al. (1988) compared VA indoors and outdoors facing the sun (106 cataractous eyes of 78 patients). The sun was 20–45 degrees above the horizon and directly above the VA chart. Altogether, 76% of cataractous eyes had an indoor vision of 0.5 or better. When facing the sun, only 31 % of eyes reached this VA. Eyes with a VA of less than 0.25 indoors accounted for only 2.8% but facing the sun 29%. The average difference between indoor VA and outdoor (facing the sun) was 3 Snellen lines. The study did not include healthy eyes.

2.14 Subjective reports on visual disability

Effect of cataract surgery on visual disability has been examined by comparing various visual parameters and patients' subjective visual function pre- and postoperatively. Monestam and Wachtmeister (1999) found that preoperative subjective visual disabilities (subjective reading, TV watching, distance estimation and ability to orientate in unfamiliar surroundings) and VAs in the better eyes were significantly correlated. McGwin et al. (2003) studied VA, contrast sensitivity, glare sensitivity and subjective Activities of Daily Vision Scale (ADVS) score in 245 cataract patients. Of these, 156 had cataract surgery and 89 preferred delaying the operation. Subjective ADVS score after surgery was significantly correlated with VA improvement. Contrast sensitivity improved and glare sensitivity decreased after surgery, and both were independent predictors of ADVS score improvement. Those having no surgery had no improvement in any of the four parameters. Superstein et al. (1999) found that in cataract patients ADVS was correlated with objective visual performance, which was measured as VA and spatial contrast sensitivity in the presence of glare. Uusitalo et al. (1999) reported low correlation (0.17) between changes in the visual-functioning index (VF-7) and VA in the operated eye of cataract patients. VF-7 a was stronger predictor than VA of patient satisfaction after cataract surgery. Moreover, Pager et al. (2004) noted that VA is an inadequate measure of relevant surgical outcomes of cataract extraction. Broman et al. (2002) reported that monocular or the better eye's worsening weakened life quality measured with the subjective scale NEI-VFQ-25. In cataract patients, low acuity explained most of the low scores in the questionnaire, but those with glaucoma or diabetic retinopathy had low scores independent of acuity. According to Monestam and Wachtmeister (1998), women experience a higher degree of visual problems preoperatively than men with the same preoperativeVAs.

3. Aims of the study

The main goals were to determine the visual acuity (VA) level at which patients undergo cataract surgery and to evaluate the repeatability of VA and refractive error measurement in clinical settings.

Specific aims were to investigate:

- the extent of vision loss during an extended wait after referral for cataract extraction (I).
- the proportion of the life expectancy of elderly patients comprised by the long waiting time (I).
- the change in preoperative VA in the time period from 1982 to 2000 (II).
- the degree of variation in the measurement of VA in clinical settings (III).
- the misclassification of VA in borderline cases in medico-legal situations (III).
- the difference in VA over two consecutive measurements required to indicate a change in VA in different VA levels (III).
- the degree of variation in the refractive error measurement (REM) in clinical settings (IV).
- the effect of variation in REM on VA values (III,IV).
- the difference in two REM results required to indicate the need for change of spectacles (IV).

4. Patients and methods

4.1 Patients in prospective studies (I, III, IV)

To investigate change in VA during waiting time for cataract surgery in 1997 (I), 141 consecutive cataract patients with a waiting time of 3 months or more were included. Patients with incomplete information about the initial VA were excluded. Thus, the final investigation included 124 patients, 38 men (31%) and 86 women (69%), with a mean age of 77.8 years (range 48–96 years) (Table 3). The average waiting time for surgery was 13.2 months, varying from 3 to 27 months. Comparison of VA at referral and on the day before surgery was made both for the eye to be operated on and for the fellow eye, of which 95 were phakic, 27 pseudophakic and two completely blind. Altogether, 12% of the eyes referred for surgery had glaucoma. Five of the patients had diabetes (one insulin-dependent) without signs of major retinopathy. Age-related macular degeneration had been diagnosed in 5 eyes. Other pathological conditions included corneal opacities and high myopia. Of the operated eyes 88 (71%) showed no ocular pathology other than cataract.

4.2. Patients in study of preoperative visual acuity in 1982 to 2000 (II)

To investigate preoperative VA of patients undergoing cataract surgery during the last two decades (II), data were collected from the patient records at Vaasa Central Hospital and Selkämeri District Hospital for years 1982, 1985, 1990, 1995 and 2000. A sample of 81 consecutive cataract operations was examined for each of the years. In 1982, this sample corresponded to 50% of all cataract surgeries in the region. In subsequent years, the sample size was kept unchanged. From 1982 to 1985, all cataract surgery in the district was performed at either Vaasa Central Hospital or Selkämeri Hospital. From 1990 to 2000, some cataract operations were performed at two other clinics as well. The hospitals from which the samples were taken cover, however, 60–80% of all operations carried out in the region during the years in question.

The sample overall comprised 405 operations on 397 patients. The mean age of the patients was 75.7 years (men 73.4 years, women 76.8 years, range 37–97 years). Yearly mean ages varied from 73.7 years (1990) to 77.6 years (2000). Men accounted for 31% of the patients, women for 69%. The mother tongue of 54% of the patients was Swedish. The remaining 46% were Finnish speaking. Residents of Vaasa proper accounted for 37% of patients. Accordingly, Vaasa was over-represented in relation to the surrounding rural areas by 11%.

In 1982, all operations were performed using an intracapsular extraction (ICCE) technique without intraocular lens (IOL) implantation. In 1985, extracapsular extraction (ECCE) with IOL implantation was the predominant procedure. In 1990, all procedures were of the ECCE type. In 1995, phaco-emulsification (PHACO) was the most common technique. In the sample for 2000, the PHACO technique was used in all but one procedure.

To investigate repeatability and random measurement error in VA measurement (III) and repeatability (test-retest variability) of REM (IV), 81 patients referred for cataract surgery to Vaasa Central Hospital or referred for consultation to the first author's office were included (Table 3). Of the eyes, 41 had cataract, 36 were pseudophakic and healthy were 4 eyes. If a patient had two identically affected eyes, only the results of the right eye were included. In addition, 18 persons of the hospital staff (nurses or office personnel) with healthy eyes were examined for comparison. The total series included 99 eyes of 99 persons (Table 3).

Table 3. Patients, main objects of study, and measurements

	Study I	Study II	Study III	Study IV
Number of patients and eyes	124	405	99	
Mean age (years); range	77.8; 48–96	75.8; 37–97	70.9; 26–89	
Women, %	69	69	73	
Main object of study	Cataractous eyes	Cataractous eyes	Cataractous (n=41) pseudophakic (n=36) and healthy eyes (n=22)	
Main object of measurement	VA, life expectancy	VA	VA measurement, precision and accuracy	Refractive error measurement, precision and accuracy
Ocular comorbidity	Assessed	Assessed	Assessed	
Patient's general morbidity	Assessed	Assessed	Assessed	

4.3. Methods

4.3.1 Measurement of visual acuity (I, II, III, IV)

VAs were measured as Snellen decimal values. To calculate mean VAs, decimal values from acuity charts were converted to logarithmic values (logMAR) (Holladay & Prager 1991, Holladay 1997). Because of the inaccuracy associated with measurement of very low VA, the lowest value was set to 0.01 (counting fingers at 0.5 m), equivalent to 2.0 logMAR. The expression log line is used for 0.1 logMAR unit.

Visual abilities of patients (Studies I and II) were also investigated with reference to the World Health Organization classification of visual handicap. According to the WHO definition, visually handicapped patients were those who at the time of evaluation had VA below 0.3 in their better eye. Legally blind patients were those whose VA in the better eye was below 0.05 (WHO Study Group 1972).

Any Snellen value ($V_{Snellen}$) can be converted to logMAR by calculating minus $\log_{10}(V_{Snellen})$ = logMAR. Similarly logMAR can be converted back to Snellen values by calculating $V_{Snellen} = 10^{-\,logMAR}$. The calculations for conversion between Snellen and logMAR values were performed according to this principle (Holladay & Prager 1991). Appendix demonstrates calculations of VA change for an imaginary patient group.

4.3.2 Comparison of visual acuities (III, IV)

In Studies III and IV, the BCVAs and refractive errors obtained at the initial examination and at the re-examination were compared. The first examination was performed by the referring ophthalmologist (n=19), optician (n=4) or the first author (n=76). There were eight different referring professionals (seven eye specialists, one optician), eight different examination sites and six different distance acuity projectors (Rodavist 2, Rodamat, Magnon CP 670, Magnon CP 600, Takagi, Topcon ACP 5). The first and second examinations were performed at different sites in 86/99 cases (87%). The results of the first examination were not disclosed at the second examination. The VA projector charts had an examination distance of 6 m. VAs were initially recorded in Snellen decimal notation and then converted to logMAR by the first author prior to further calculations.

VAs were recorded as correctly or partly correctly read lines. The line was recorded as correctly read when 75% of the optotypes of the line were correctly identified. When more than 25% but less than 75% of the line was correctly read, the author used the expression “partly read line”, which in calculations received the mid-value between the partly read line and one line below it. Because variation in REM was expected, all VA measurements were performed after rerefraction by retinoscopy and conventional subjective refraction (Michaels 1975d).

The VA projectors had 3–5 (average 4.0) optotypes per line in the VA range of 0.3–1.3, which was used in this study. The line size progression varied between 0.046 logMAR and 0.125 logMAR. The average was 0.088 logMAR. The largest difference (0.125 logMAR) in most charts was between the lines 0.3 and 0.4.

In the cataract group, the comparisons were made between two preoperative examinations of the operated eye or between the initial and final examinations of the cataractous non-operated fellow eye. Pseudophakic eyes included were fellow eyes of patients who came for second eye cataract surgery.

The average time between the first and second examinations was 45 days (range 9–132 days). In ten cases, the second examination was performed more than 75 days after the first one.

4.3.3 Measurement and remeasurement of refraction (III, IV)

Spherical and cylinder power were measured by retinoscopy and subjective conventional refraction (Michaels 1975d), and axis by Jackson's cross cylinder. The first refractive error measurement (REM 1) and the second measurement (REM 2) were performed in different sites at 86/99 cases (87%). Differences in REM were calculated by Harris' matrix vector method (Harris 1990a). Keating's formula (Keating 1980) was used to convert the REM difference back to normal clinical notation.

The repeatability in REM was expressed as coefficient of repeatability (CR), which is 1.96 times the standard deviation of the differences between test and retest values (Bland & Altman 1986, Bland 1988, MedCalc Manual 2005). The comparisons were first performed with spherical equivalents (SE), and CR was calculated. Because SE loses information on cylinder power and direction, the results in the first and second REMs were converted from conventional (sphere-cylinder-axis) notation to three-dimensional vector matrix as described by Long (1976) and Harris (1990a), and the differences between test and re-test measurements were calculated (Harris 1990b,c). The power vectors describe dioptric powers in three matrix values, which Harris expressed as vectors f11, f12 and f22. These can also be referred to as vertical (V), torsional (T) and horisontal (H) components (Keating 1986). The mean values for vectors were calculated as matrix column values described by Kaye & Harris (2002). Appendix shows calculations of the mean for refractive values RV1, RV2 and RV3 and the difference between RV1 and RV2. To study the variability, the differences in results of measurements 1 and 2 were squared and converted to CRs as described by Bland and Altman (1986), Bland (1988) and the MedCalc Manual (2005). For SE values, which are one-dimensional, CR can be calculated conventionally. The significance of differences between groups in test and re-test values and CR for three-dimensional vector values was evaluated using multivariate statistics as described by Harris (1990b).

4.4 Estimate of defocus effect on visual acuity (III, IV)

If the results in REM 1 and 2 differ from each other, one or both are incorrect. When seeing with an incorrect correction the eye is in defocus. If the correct refractive error is the mid-value (average) between obtained REM values 1 and 2, which is the expected value (when normal distribution is assumed), both corrections are in equal defocus compared with the mid-value between REM 1 and 2. If one of the REM values is correct, the other is in defocus equal to the difference between REM 1 and 2. Defocus equivalent (DE) is proportional to the blur circle caused by refractive error, and it indicates the decreased VA without correction (or incorrect refractive correction) as a function of refractive error (Holladay et al. 1991). DE value of the difference in results of REM 1 and 2 was calculated from a three-dimensional vector value difference and converted back to conventional notation by Keating's method (Keating 1980). DE was then calculated from this conventional value (REM 1 and 2 difference) according to Holladay et al. (1991) as the sum of the absolute value of SE plus half the absolute value of the cylinder. By combining DE and information received in empirical studies (Table 2), a formula can be devised that gives an estimate of VA decrease also in eyes having BCVA lower than 1.0. Each ray reaching the retina in a defocused eye has a widened point spread. This point spread widening can be calculated using empirical studies expressing decrease of normal VA by defocus. The average of literature values (Table 2) was calculated and interpolated, and the inverse of VA values with defocus gives the absolute value of weakened resolution by DE. An eye with BCVA 1.0 and refraction error 0 has a resolution of 1 min of arc, and an eye with refraction error of 0.5D has VA 0.7 and thus a resolution 1/0.7 = 1.4 min of arc. The decrease of resolution by 0.4 min of arc is the absolute value of resolution decrease by 0.5D defocus. An eye having VA 0.5 has a resolution of 2 min of arc, and with 0.5 D defocus this resolution decreases to 2.4 min of arc. Rays entering the retina in a defocused eye have a widened point spread by the magnitude caused by defocus. Because DE is proportional to the blur circle caused by refractive error, it can be used for estimation of VA decrease in a defocused eye. A general formula can be given as follows: $1/VA = 1/\ (1/VA_{BC} + 1/\ VA_{DE} -1)$, where VA is visual acuity with defocus, VA_{BC} is visual acuity with best correction and VA_{DE} is visual acuity of the normal eye with defocus DE. A closer demonstration of this principle is included in Appendix 3 and 3b. This is an approximate estimation, like the empirical values in Table 1. It is calculated for a certain pupil size, an average observer and an average visual task with high contrast.

4.5 Statistical methods

For quantitative values, the independent two-way *t*-test was used to determine significances of differences (Studies I and II). For qualitative variables, the chi-squared test was used. Linear regression was used to estimate yearly changes in VA before operation and incidence of operations. Snellen VA decimal values were converted mathematically to logMAR values. Differences, averages and standard deviations (SDs) were calculated in logMAR units. To describe the yearly changes in preoperative VA and incidence of cataract extractions a linear regression model was applied. Variability was calculated as the SD for paired differences between measurements 1 and 2, as described by Bland and Altman (1986), Bland (1988) and the MedCalc Manual 2005), and expressed as coefficient of repeatability (CR) and standard deviation of measurement error (SDME). Statistical calculations were performed using SSPS 11.5 version. Comparisons of REM between VA groups were made with the non-parametric Kruskall-Wallis test or one-way analysis of variance (ANOVA) (SSPS for Windows 11.5). The normality of difference distribution between paired values was calculated by the Kolmogorov-Smirnov and Shapiro-Wilk test. The 95% confidence intervals (95% CIs) for three-dimensional REM differences and the significance of differences between groups in test and retest values were calculated using multivariate statistics, as described by Harris (1990b).

5. Results

5.1 Grade of vision loss in patients awaiting cataract surgery (I)

The amount of vision loss in patients waiting for cataract surgery was studied in 124 consecutive patients referred for cataract surgery and having reliable information on VA. The average waiting time for surgery was 13.2 months, varying from 3 to 27 months.

At the time of referral, 17 (14%) of the study (operated) eyes had a VA of 0.5 or better, and 57 eyes (46%) had a VA below 0.3. On the day before surgery, only one eye (0.8%) had a VA of 0.5 and 95 eyes (77%) had a VA below 0.3 (Table 4).

At the time of referral, 82 patients (66%) saw better than 0.5 with their better eye. During the waiting period, their number decreased to 51 (41%). The number of patients who saw worse than 0.3 with the better eye (classified as visually handicapped according to WHO, 1972) increased from 10 (8%) to 26 (21%) (Table 4).

Table 4. Visual acuity of the operated eye and the better eye at the time of referral and on the day before surgery

	Operated eye				Better eye			
Visual acuity	Referral		Preoperative		Referral		Preoperative	
(Snellen)	n	%	n	%	n	%	N	%
≥0.5	17	14	1	0.8	82	66	51	41
0.3–0.45	50	40	29	23	32	26	47	38
<0.3	57	46	94	76	10	8	26	21

The average VA of operated eyes at the time of referral was 0.68 logMAR (equivalent to Snellen 0.2) (Table 5). The average worsening of VA during the waiting time was 0.28 logMAR units ($p<0.0001$, one-tailed *t*-test). In about half (59/124, 48%) of the operated eyes, the worsening in VA was insignificant (less than 0.2 logMAR units), while 30% (37/124) of the eyes experienced worsening by 60% or more of the initial VA (more than 0.4 logMAR units). Patients who were 75 years or older had slightly less change in VA than patients under 75 years of age (NS, $p=0.07$, one-sided *t*-test).

The unoperated fellow eyes worsened by 0.14 logMAR. Only a weak positive correlation existed in visual changing speed in the operated and unoperated fellow eyes. The correlation coefficient was 0.2 for the 95 paired eyes, and the slope for linear regression was 0.50. The pseudophakic fellow eyes also worsened, the decrease was 0.07 logMAR (NS, p=0.06, two-sided *t*-test) (Table 5).

Table 5. Visual acuity (VA) at the time of referral and preoperatively, logMAR and equivalent Snellen values

	VA at referral, mean logMAR (Snellen)	VA preoperatively, mean logMAR (Snellen)	Change in mean VA, logMAR *
All operated eyes	0.68 (0.21)	0.96 (0.11)	0.28
Unoperated eyes	0.33 (0.48)	0.47 (0.34)	0.14
Operated fellow eyes	0.17 (0.68)	0.24 (0.57)	0.07

* positive logMAR difference means a decrease in VA

5.2 Rapidity of visual acuity change

The rapidity of visual change calculated individually as the mean logMAR change per year was 0.27 logMAR. When the operated eyes were ranked according to the changing speed in the VA into four quartiles (Figure 1), the mean value in the fastest quartile was 0.75 logMAR per year. The slowest quartile was slightly negative, which means that there was virtually no change during the waiting time. No significant differences were observed in VA change in the different VA groups ≥0.5, 0.3–0.45, and <0.3 (one-way ANOVA).

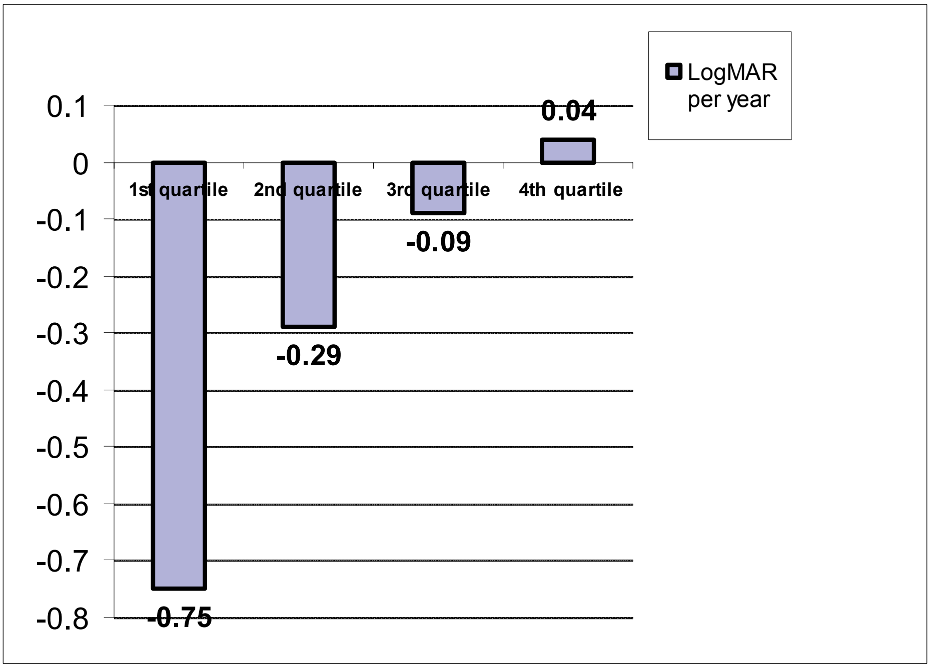


Figure 1. Rapidity of visual acuity change per year (logMAR) *
* The minus sign is used to express a decrease in VA.

5.3 Life expectancy of patients after referral for cataract surgery

Because the mean waiting time, 13 months, is likely a considerable part of the expected remaining life of elderly people, an estimate of the life expectancy of study patients was determined using the Finnish life statistics provided by the Central Bureau of Statistics, Finland (1995). The values were calculated individually for each patient according to age and sex using Finnish averages.

The mean age of the men at the time of the operation was 74.3 years, and their average life expectancy was 10.0 years. The average age of the female patients was 79.4 years and their life expectancy 9.3 years. Despite the age difference, the life expectancies of both sexes were close to each other. An estimated 8% of men and 5% of women would live for more than 20 years, while the respective figures for those with a life expectancy of less than 5 years were 16 % and 19 %.

The mean waiting time at the time of referral for all patients was 13% of the life expectancy, 12% for men and 14% for women. One-third of the patients (31%) had to wait 10–15% of their remaining life time, and 5% more than 25%. In 11% the waiting time was less than 5% of their expected life span (Figure 2).

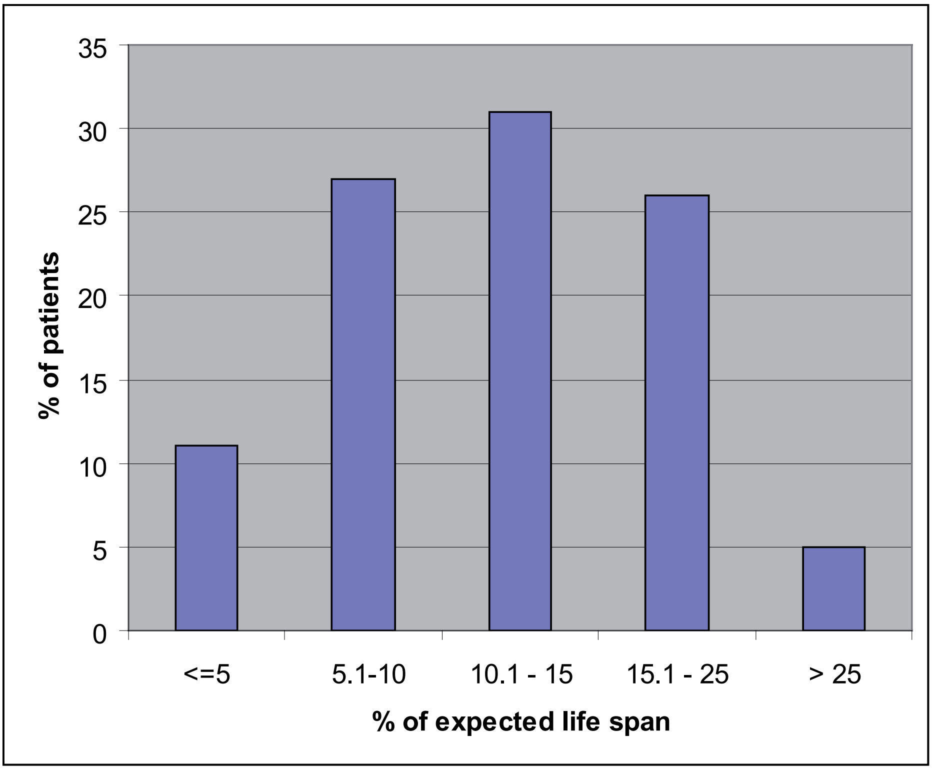


Figure 2. Length of waiting time relative to expected life span of patients after referral

5.4 Preoperative visual acuity of patients undergoing cataract surgery during the last two decades (II)

5.4.1 Indications for surgery and change in extraction methods

Indications for surgery and the type of cataract extraction method were evaluated in 81 consecutive operations in each of the study years 1982, 1985, 1990, 1995 and 2000. The main indication for all surgeries was worsening of vision in the operated eye. Glaucoma was an additional indication in three cases in which cataract extraction was expected to also have a favourable effect on the course of glaucoma. In four cases, cataract had been caused by trauma.

Within the last two decades the technique of cataract extraction had changed from 100% intracapsular cataract extraction technique (ICCE) in 1982 to 100% extracapsular cataract extraction (ECCE) in 1990 and further to 99% extracapsular cataract extraction by phacoemulsification (PHACO) in 2000 (Table 6). The numbers of second-eye operations had increased markedly during the study period. In 1985, 11% of the operations were on the second eye; in 2000, the corresponding figure was 36% (Table 6).

Table 6. Operation technique and frequency of second-eye operations in 1982-2000

Year	Operations reviewed (n)	ICCE (%)	ECCE (%)	PHACO (%)	Second eye operations (%)
1982	81	100	–	–	14.8
1985	81	42	58	–	11.1
1990	81	–	100	–	25.9
1995	81	–	13.6	86.4	30.9
2000	81	1.2	–	98.8	35.8

5.4.2 Preoperative visual acuity in 1982–2000

In 1982 and 1985, preoperative VA was mostly low (Figure 3), below 0.1 in 72% and 69% of the operated eyes, respectively. In 1995, with the PHACO technique predominating, preoperative VA was below 0.1 in 26% and in 2000 in 11% of operated eyes. Between 1982 and 2000, the proportion of operated eyes in which preoperative VA was better than 0.3 increased from 6% to 44%. The proportion of operated eyes with VA≥0.5 was low, but increased from practically zero in 1982 to 7.4% in 1990 (Figure 3).

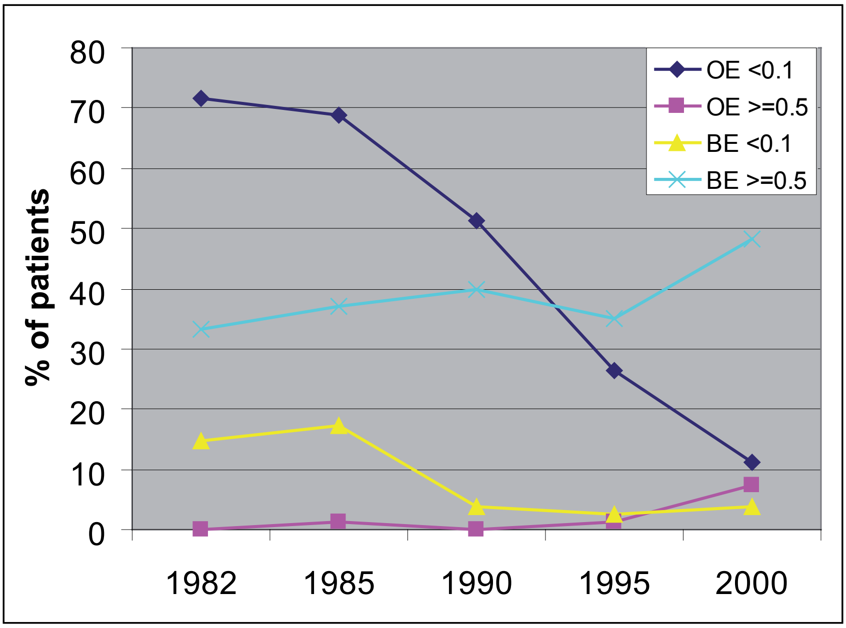


Figure 3. Preoperative best corrected visual acuity (BCVA) in the operated eye (OE) and in the better eye (BE) in 1982–2000

In 1982 and 1985, the average VA in the operated eye, in logMAR units, was 1.56 and 1.48, respectively (corresponding to Snellen 0.03) (Table 7). In 1995, the average VA in the operated eye was 0.95 logMAR (0.11), and in 2000 it was 0.71 logMAR (0.20). Between 1982 and 2000, the average preoperative VA in the operated eye had increased by 0.85 logMAR units or 8.5 lines. The increase in preoperative VA in the operated eye per year was 0.049 logMAR (a 0.5 log line, linear regression relating to all values, correlation coefficient (r^2) 0.29).

In second-eye operations, the average VA in the operated eye was significantly better than the average preoperative VA in the first-eye operations (1.02 logMAR vs. 1.23 logMAR; p<0.001). Patients in the Vaasa urban region had slightly better preoperative VA on average than patients in the surrounding rural areas (1.11 logMAR vs. 1.25 logMAR; p=0.009).

Table 7. Preoperative mean visual acuities (MVA) in the operated eye (OE) and in the better eye (BE); p for change is as compared with MVA 1982

Year	MVA OE logMAR, (Snellen)	MVA BE logMAR, (Snellen)	* CG (for p-value)	p OE, change	p BE, change
1982	1.56 (0.03)	0.64 (0.23)			
1985	1.48 (0.03)	0.64 (0.23)	1982	0.34	
1990	1.22 (0.06)	0.45 (0.36)	1982	<0.001	0.005
1995	0.95 (0.11)	0.47 (0.33)	1982	<0.001	0.01
2000	0.71 (0.20)	0.37 (0.43)	1982	<0.001	<0.001
All	1.19 (0.07)	0.52 (0.34)			

* CG : comparison group for change (independent *t*-test, two-sided)

The VA in the better eye, which indicates a patient's ability to see in everyday life, was in many cases much better than the VA in the operated eye (Table 7, Figure 4). Patients who, in terms of the WHO classification (1972), had preoperatively been visually handicapped (VA in better eye <0.3) because of cataract accounted for 47% of patients in 1982. The corresponding proportion for 1995 was 29%, and for 2000 only 15%. A VA of ≥0.5 in the better eye had been found in 33% of cases in 1982, and 48% in 2000. Some of the patients entered the second-eye operation with improved vision in the better eye as a consequence of the first surgery. In 73% of persons (range 57–100%) entering the second-eye operation, VA of the better eye was ≥0.5 as compared with 28% (range 16–35%) of persons in the first-eye operation (Table 8).

Table 8. Preoperative visual acuity 0.5 (Snellen) or better in the better eye in patients undergoing first- or second-eye surgery

Year	VA ≥ 0.5 in better eye in first-eye surgery	VA ≥ 0.5 in better eye in the second-eye surgery
1982	18/69 (26%)	9/12 (75%)
1985	21/72 (29%)	9/9 (100%)
1990	21/60 (35%)	12/21 (57%)
1995	9/56 (16%)	19/25 (76%)
2000	18/52 (35%)	21/29 (72%)
Total	87/309 (28%)	70/96 (73%)

In 1982, the average preoperative VA in the better eye was 0.64 logMAR, in 2000 0.37 logMAR, corresponding to a difference of 2.7 log lines. The yearly increment is 0.15 log lines (linear regression relating to all values). Those living in urban Vaasa had a slightly better preoperative VA than those living in surrounding areas (0.46 logMAR vs. 0.55 logMAR, $p=0.06$, independent *t*-test, two-sided). In the ICCE group, the average VA in the better eye was 0.66 logMAR, in the ECCE group 0.49 logMAR and in the PHACO group 0.43 logMAR ($p=0.001$ and $p<0.001$, respectively, compared with the ICCE group, independent *t*-test, two-sided). The corresponding Snellen values for the better eyes are 0.22 for the ICCE group, 0.32 for the ECCE group and 0.37 for the PHACO group. In second-eye operations, VA in the better eye before surgery was 3.3 log lines better than in first-eye operations.

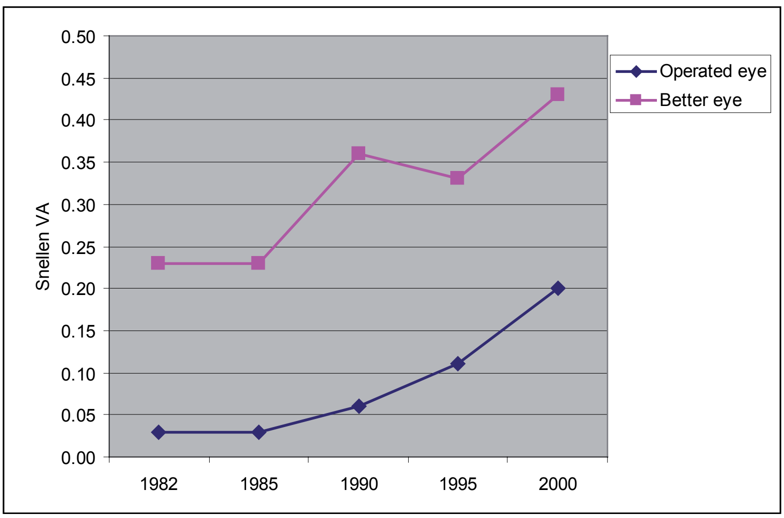


Figure 4. Average Snellen visual acuity in 1982–2000 in the operated eye and the better eye

5.4.3 Correlation between visual acuity and the number of operations performed

At the beginning of the study period, annual incidences for cataract surgery were 1.0 operation per 1000 inhabitants overall and 6.5 operations per 1000 inhabitants aged 63 years or older. At the end of the study period, the respective annual incidences were 7.2 and 39.9 operations.

Figure 5 shows the change in average preoperative VA (Snellen) in relation to incidence of cataract operation per 1000 inhabitants. The corresponding linear regression statistics are average logMAR VA of the operated eye = 1.60–0.134* number of operations per 1000 inhabitants. The 95% CI for the regression gradient is –0.16 to –0.11. An increment of one operation per 1000 individuals corresponds to an average improvement in VA in the operated eye of 1.3 log lines (95% CI 1.1 to 1.6). The corresponding statistics relating to the average logMAR VA of the better eye = 0.64–0.040* number of operations per 1000 inhabitants, and 95% CI for the gradient of –0.022 to –0.057. The increase in VA of the better eye per increment of one operation is therefore markedly lower, 0.4 log lines per 1000 inhabitants (95% CI 0.22 to 0.57 lines).

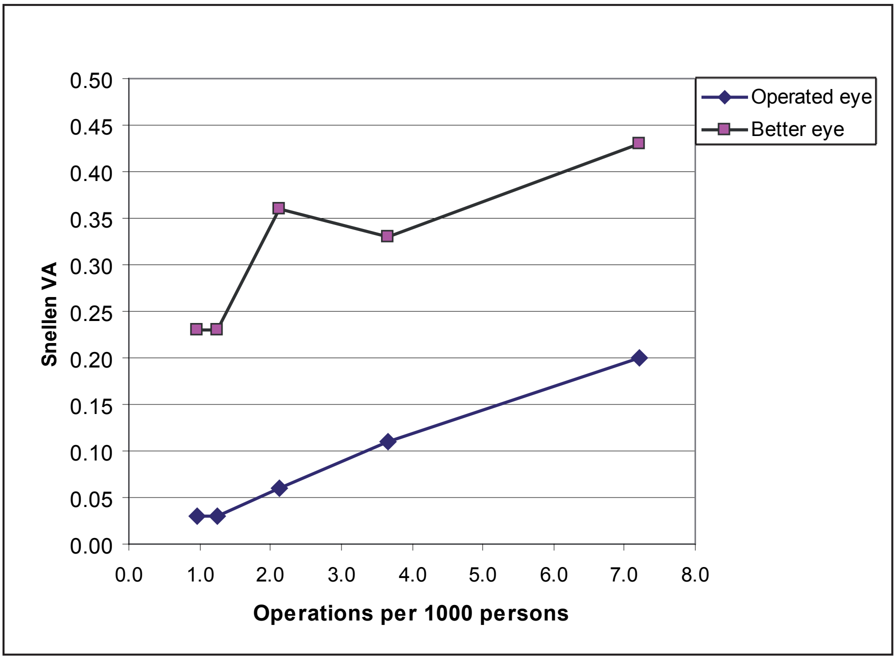


Figure 5. Average preoperative Snellen visual acuity (VA) dependence on operation incidence in operated and better eyes

5.4.4 Ocular and general morbidity

Of the 309 patients undergoing first-eye operation, 106 (34.3%) were suffering from ocular disease other than cataract. Retinal disease and glaucoma were the most common. The proportion of other ocular diseases varied from 32% to 42% (NS) in 1982–2000. Patients had been recorded as suffering from cardiovascular disease, diabetes (including dietary diabetes), endocrinological disease, pulmonary disease, rheumatic disease and malignancy. Some had been received medical psychiatric therapy. The proportion of general diseases varied from 62% to 83% (NS) (Table 4, II).

5.5 Repeatability of visual acuity determination (III)

Repeatability of VA determination in a clinical environment in cataractous, pseudophakic and healthy eyes was estimated in a test-retest setting for 99 (41 cataractous, 36 pseudophakic and 22 healthy) eyes of 99 persons. Only eyes with a VA of 0.3 or better were included. Based on BCVA, the eyes were divided to three subgroups: ≥0.7, 0.5–0.65 and 0.3–0.45. The mean VAs in these groups were 0.03 logMAR (equivalent to Snellen 0.93), 0.24 logMar (Snellen 0.58) and 0.41 logMAR (Snellen 0.39), respectively.

The second examination gave 0.036 logMAR better VA values than the first one. The difference was significant ($p<0.05$). The mean difference in VA was smallest in the best-seeing eyes, 0.01 logMAR (NS), and the largest mean difference, 0.08 logMAR, was in the VA group of 0.5–0.65 (Table 9). If the second examination was delayed by more than 75 days (10 eyes), the average VA was 0.02 logMAR better in the latter examination.

Table 9. Mean difference, estimated standard deviation of measurement error (SDME) and coefficient of repeatability (CR) of repeated visual acuity (VA) measurements (logMAR)

VA group	N	Mean difference and 95% CI of VA	Estimated SDME of VA	CR
All	99	–0.036±0.017	0.064	0.18
VA >0.7	59	–0.014±0.016	0.044	0.12
VA 0.5–0.65	18	–0.079±0.047	0.085	0.24
VA 0.3–0.45	22	–0.060±0.047	0.086	0.24

The differences in VA between examinations one and two in logMAR units as plotted against the mean VA (logMAR) in the two examinations are shown in Figure 6. The differences were normally distributed ($p=0.15$, Shapiro-Wilk test)

(Figure 7). Standard deviation of measurement error (SDME) indicates the expected difference between the measured value and the true value of VA. SDME for all eyes was 0.06 logMAR, for the best acuity group 0.04 logMAR and for the lower VA groups (VA 0.3–0.45 and 0.5–0.65) 0.09 (Table 9). The highest variability was in the lower VA groups, CR (95% limits of difference between two measurements) 0.24 logMAR, and the smallest in the best-seeing group (VA ≥0.7), 0.12 logMAR. For all eyes the variability was 0.18.

A difference of less than 0.1 logMAR occurred in 72/99 eyes (73%), in cataractous eyesless frequently (63%) than in the other groups. Exactly the same VA value in both tests was obtained in 23/99 eyes (23%), specifically in 6/41 cataractous eyes (15%), 8/36 pseudophakic eyes (22%) and 9/22 healthy eyes (41%).

In 10 eyes, the VA results in the first and second examinations were on different sides of the Snellen value 0.5 required for driving a car in Europe, 9 eyes being cataractous and one pseudophakic. In 9 of these 10 cases, VA was better in the second examination. In cataractous eyes, a difference of 2 log lines was found in 3/41 eyes.

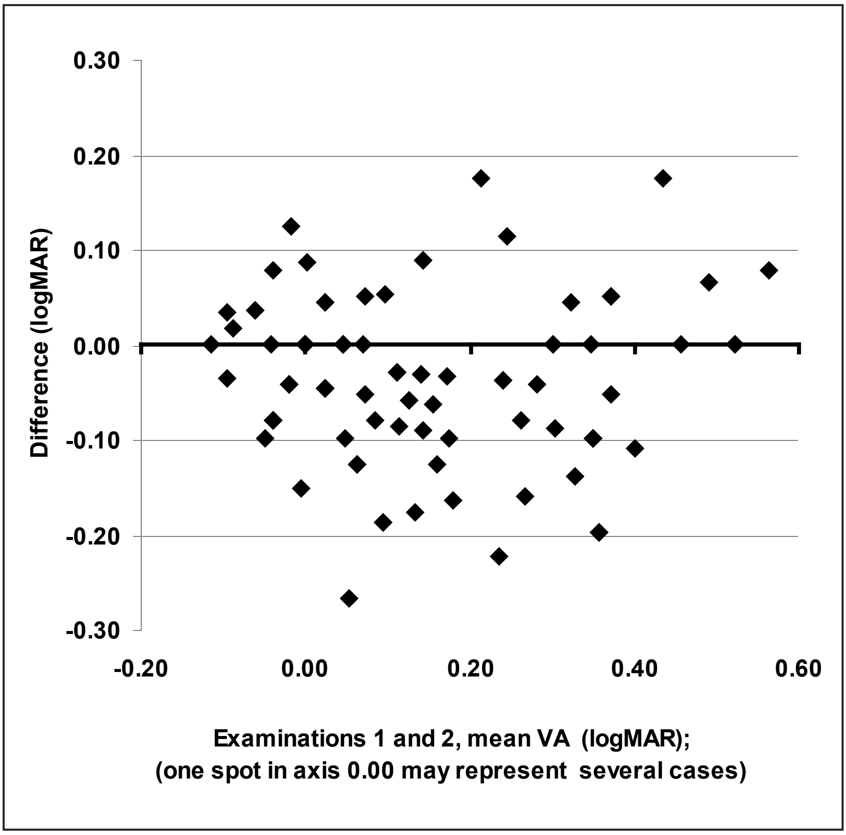


Figure 6. Difference in visual acuity in examinations 1 and 2 as plotted against their mean (logMAR)

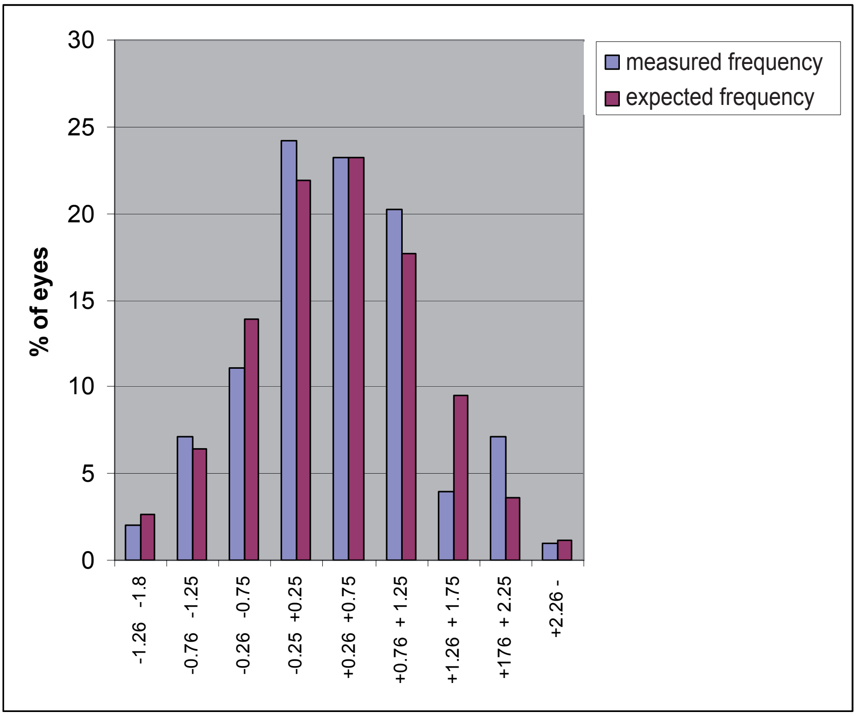


Figure 7. Measured and expected frequency (normal distribution) of difference in visual acuity in examination 1 and 2 (logMAR)

5.6 Repeatability of refractive error measurement (IV)

Repeatability of REM in a clinical environment was measured in the same sample of 99 persons included in Study III (41 cataractous, 36 pseudophakic and 22 healthy eyes) by retesting refractive error while masked to the result of the first measurement. Only eyes with a VA of 0.3 or better were included, and the eyes were divided to three VA subgroups as in Study III: ≥0.7, 0.5–0.65 and 0.3–0.45.

5.6.1 Distribution of ametropias

The spherical equivalent of refractive errors ranged between –8.5 and +3.8D (Table 10). Ametropias exceeding ±3D were found in 6/99 eyes. The smallest number of ametropias exceeding ±3D was in the pseudophakic group (1/36). No statistically significant differences were present in SE between cataractous, pseudophakic and healthy eyes or between VA subgroups (one-way ANOVA). Cylinder values exceeding 2D were found in 8/99 eyes, most of these in the pseudophakic group (5/36).

Table 10. Distribution of ametropia, mean refractive error and mean visual acuity in the study eyes at the first examination

Group (n)	Ametropia (SE) >±3D (n)	Cylinder power >±2D (n)	Mean SE (D) (range)	Mean visual acuity, logMAR; (Snellen acuity)
Cataract (41)	2	3	+0.40 (–8.5– +3.4)	0.294 (0.51)
Pseudophakia (36)	1	5	–0.52 (–3.8– +1.9)	0.099 (0.80)
Healthy eyes (22)	3	0	–0.45 (–6.1– +3.8)	–0.014 (1.03)
All eyes (99)	6	8	–0.12 (–8.5– +3.8)	0.154 (0.70)

5.6.2 Repeatability of refractive error measurement in spherical equivalents and three-dimensional vectors

The variability of results in REM 1 and 2 is described in Table 11 and in Figures 8, 9 and 10. Figure 8 shows the test-retest differences in spherical equivalents (SE) in REM 1 and 2. Repeatability (CR) for all eyes for V (vertical), T (torsional) and H (horizontal) vectors was ±0.74D, ±0.34D and ±0.93D, respectively (Table 11). CR for vectors (confidence regions) are plotted as ellipses in the three ortogonal planes (Figure 9). The greatest variability in subjective refraction in all groups was in the horizontal vector. It increased with decreasing VA from ±0.71D (VA≥0.7) to ±1.4D (VA 0.3 – 0.45). The least variation was in the torsional vector, ±0.34D for all eyes, ±0.32D for VA ≥0.7 and ±0.30D for VA 0.3–0.45. The average vector values for differences in test-retest values for all eyes were –0.011D (V); –0.010D (H); 0.070D (T), which are all very close to zero vector (conventionally sf –0.01D cyl –0.06D ax 9°). Differences were not significant (multivariate statistics), indicating that no systemic error ocuurred between test-retest values. In addition, all VA subgroups had very small test-retest average differences, and none of these was significant. Healthy eyes had better VAs and a more uniform REM than other eyes.

Table 11. Mean differences and coefficient of repeatability (CR) in test and retest values of power vectors vertical (V), torsional (T) and horizontal (H), spherical equivalents as well as defocus equivalents >0.5D are given for the different visual acuity (VA) groups

Group	N	Mean differences and CR				Defocus equivalent >0.5D for difference (REM1-REM2) (n)
		Power vectors (D)			Spherical equivalent (D)	
		V	T	H		
All	99	0.01±0.74	–0.01±0.34	0.07±0.93	0.04±0.74	7/99
VA ≥0.7	59	0.03±0.57	–0.03±0.32	0.06±0.71	0.05±0.51	2/59
VA 0.5–0.65	18	–0.01±0.80	0.05±0.46	0.01±0.86	0.00±0.78	1/18
VA 0.3–0.45	22	–0.02±1.1	0.00±0.30	0.13±1.4	0.06±1.14	4/22

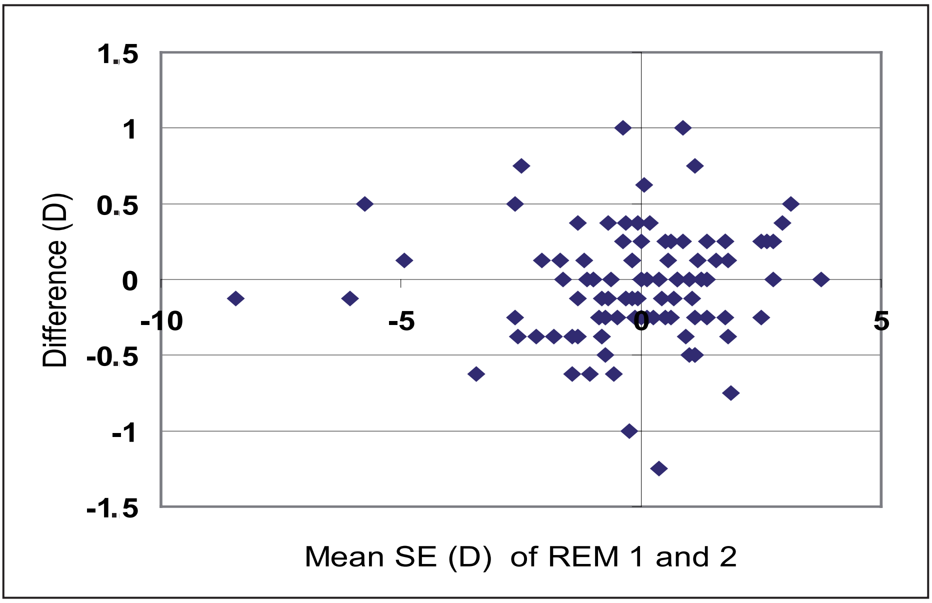
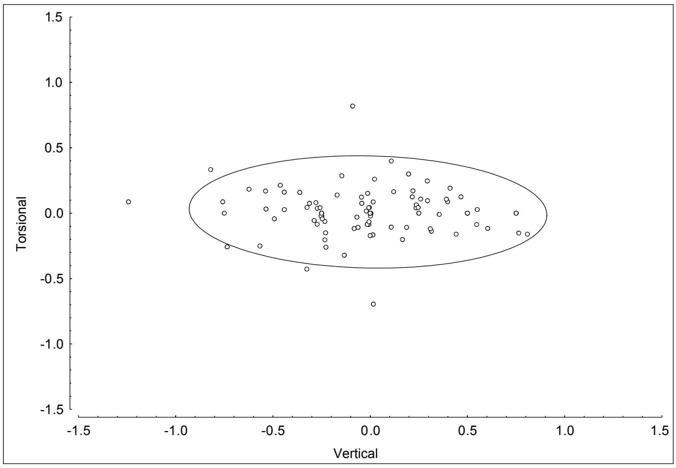
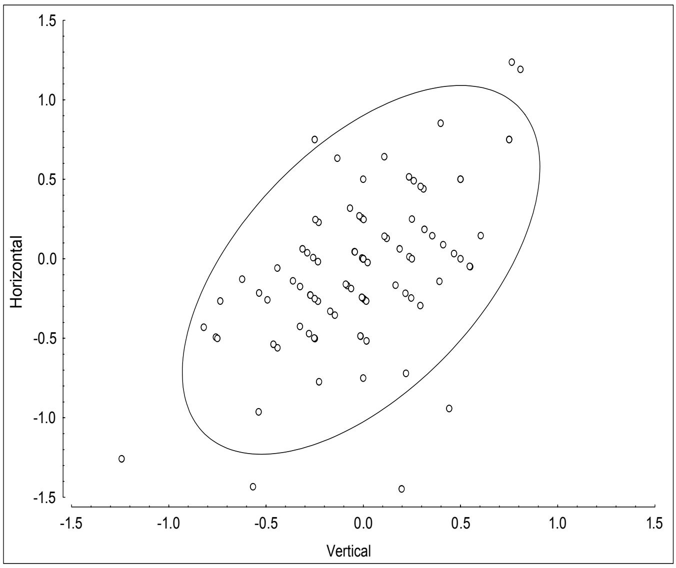


Figure 8. Test-retest differences in spherical equivalents (SE) *
* One point in axis 0 may include one or more identical SE results in REM 1 and 2.





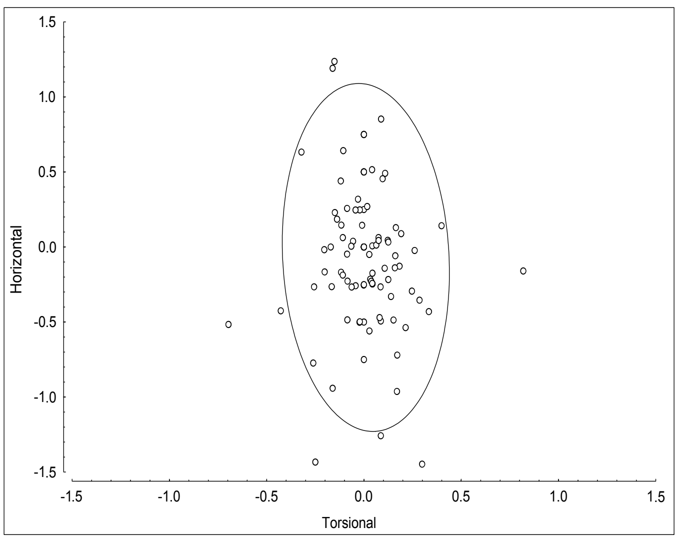


Figure 9. 95% confidence ellipses for vertical, torsional and horizontal vectors (n=99), unit D

Test-retest differences in SE are described in Figure 8. In 87/99 measurements (88%) SE was within ±0.5D; in the lowest VA group (0.3–0.45) 15/22 (68%) and in the highest VA group (≥ 0.7) 56/59 (95%). The CR of spherical equivalents for all eyes was ±0.74D (Table 11). In the lowest VA group (0.3–0.45) CR was ±1.14D and in the highest VA group (≥ 0.7) ±0.51D. No statistically significant difference was present between these subgroups (Kruskall-Wallis test). The distribution of differences between the first and second tests was slightly skewed, the latter examination being more hyperopic (significance by Shapiro-Wilk test 0.055, Kolmogorov-Smirnov test 0.011).

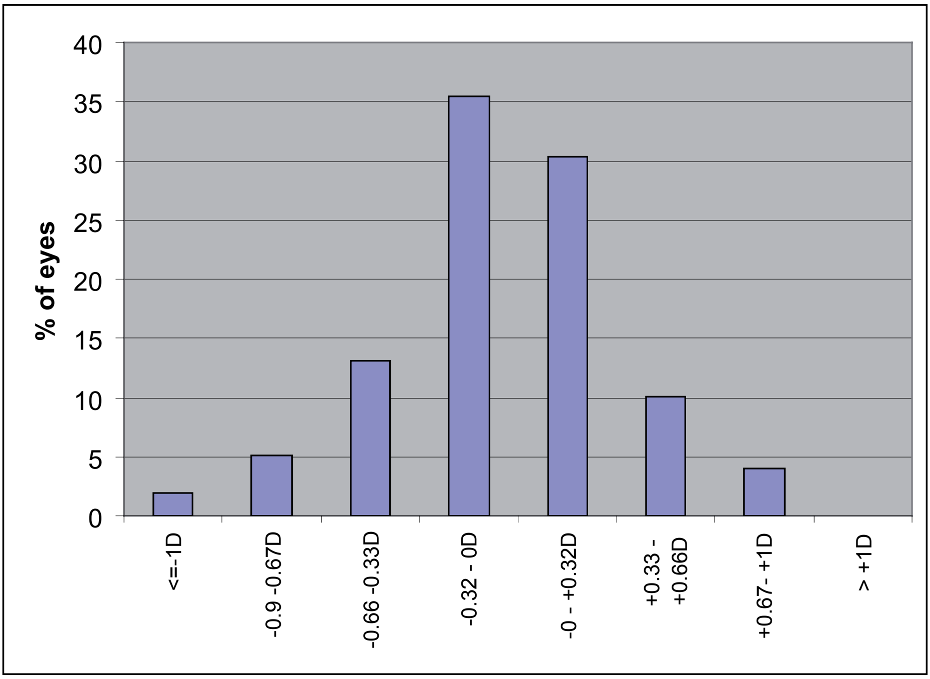


Figure 10. Distribution of differences between REM 1 and 2, spherical equivalents (D)

5.6.3 Defocus equivalent

Defocus equivalent (DE) was used to estimate the effect of REM error on VA. Differences in REM 1 and 2 were converted to DEs according to Holladay et al. (1991) in different VA groups. In eyes with good vision (VA ≥0.7) average DE was 0.40D (range 0–1.02D) and in the lowest vision eyes (VA 0.3 – 0.45) 0.71D (range 0–1.5D). The difference between VA groups was significant (p=0.001; Kruskall-Wallis test).

To determine out the effect of incorrect REM result on VA, a further estimate was made by comparing REM test-retest differences. If the paired REM values differ from each other, one or both of them are incorrect. When the REM differences were normally or near-normally distributed, the expected correct value is the midvalue (average) of REM 1 and 2. Comparison of each of the REM values to the average of each pair as DE values allows one to estimate how much REM error could decrease VA as compared with the BCVA value (logMAR values) if the best correction would have been reached. The calculation is done by using the formula given in the Methods (section 4.4). Table 12 shows the estimated average and maximum decrease (corresponding to the greatest difference in REM 1 and 2 in each VA group) as well as standard deviation. The minimum, of course, is zero in cases where REM 1 and 2 are exactly the same.

Table 12. Estimated visual acuity decrease (logMAR) due to refractive error measurement (REM) error

VA group	n	Estimated average decrease (logMAR)	Maximum decrease (logMAR)	Standard deviation (logMAR)
≥0.7	59	0.041	0.23	0.04
0.5 to 0.65	18	0.039	0.16	0.04
0.3 to 0.45	22	0.047	0.20	0.05
All	99	0.042	0.23	0.04

The expected average decrease was 0.04 logMAR or 0.4 log lines, and the range in different VA groups was quite uniform, 0.039 logMAR to 0.047 logMAR. The values corresponding to greatest difference in each VA group (maximum) were from 0.16 logMAR to 0.23 logMAR.

6 Discussion

6.1 Decrease in visual acuity while waiting for cataract surgery

Studies describing longitudinal change in cataract progression mostly concentrate on anatomical progression of cataract, with fewer studies describing changes in VA in cataractous eyes. Anatomical progress has been investigated by the LOCS II and LOCS III methods (Magno et al. 1993, 1995, The Italian-American Cataract Study Group 1994, Leske et al. 1996, 1997). The progression was faster than the incidence for the same observation period. The results are quite variable (Table 13). In a Finnish epidemiological study, Rouhiainen and coworkers (1997) examined early lens opacities and found progression of 9% in nuclear opacities, 5% in cortical opacities and 0.5% in posterior subcapsular opacities in three years using the LOCS II method.

Relatively few studies describe longitudinal change in VA in cataractous eyes. Rouhiainen and coworkers (1997) found an average decrease of 0.07 logMAR units in corrected VA in three years. Desai et al. (1999) recorded the profiles of 18 454 patients aged 50 years or older who had a mean waiting time for surgery of 7.4 months. At the entry to the waiting list, 31% had VA 6/12 or better in the surgery eye, 54% between 6/18 and 6/60 and 15% less than 6/60. Of those with VA 6/12, at the time of admission to surgery, vision had deteriorated to 6/18–6/60 in 33% and in a further 3% to below 6/60. In Study I, the average waiting time for operation in 1997 was 13 months, and the average decrease in VA in eyes referred for cataract surgery, calculated as change per year was 0.27 logMAR varying from none or little in about half of the patients to 0.75 logMAR units in the fastest quartile.

Table 13. Comparison of studies investigating cataract progression; anatomical and visual acuity changes

	Observation time	Method of observation	Progression of cataract (Regression)			
			Decrease of BCVA	Nuclear opacities %	Cortical opacities %	Posterior subcapsular opacities %
Study I	13 months, patients on waiting list for operation	BCVA Operated eyes	logMAR 0.27, all (124)			
		BCVA Operated eyes	0.75, fastest ¼ (n=31)			
		Un-operated fellow eyes	0.14, (n=95)			
Desai et al. 1999	7.4 months	BCVA Operated eyes	31% had BCVA ≥0.5 at the beginning of waiting time. Of these 33% had BCVA 0.3 – 0.1 preoperatively and a further 3% BCVA <0.1.			
Rouhiainen et al. 1997	3 years; early lens opacities	LOCS II, BCVA	logMAR 0.07	9.2	4.8	0.5
Leske et al. 1996	2 years 5 years	LOCS III		36 46		
Leske et al. 1997	5 years	LOCS III			16	55
McCarty et al. 2003	5 years			19	14	20
Italian-American Cataract Study Group 1994	3 years, group of 65 to 74 year-old patients	LOCS II		Progression		
				67	45	47
				Regression		
				6	5.5	19
Magno et al. 1993	6 months	LOCS II		Progression		
				38	28	8
				Regression		
				4	4	4
Magno et al. 1995	12 months	LOCS II		Progression		
				42	32	10
				Regression		
				5	4	2

Although anatomical progression of cataract was not classified, the finding that 50% of eyes showed no or minimal (less than 0.1 logMAR) worsening in VA per year is in accordance with previous anatomical observations (Table 13).

During the waiting period, many of the patients did, however, experience considerable worsening in their vision. At the time of referral 54%, of the operated eyes had a VA of 0.3 or better. At the time of surgery, only 24% of the operated eyes saw better than 0.3. The average worsening in all operated eyes, 0.27 logMAR units per year, means that the average VA of the operated eye was only 52% of the VA at the time of referral, e.g. from 0.3 to 0.15. In the fastest quartile, the VA decrease was 0.75 logMAR and the preoperative VA was only 17% of the initial VA. The unoperated fellow eyes had a decrease of 0.14 logMAR (VA is 72% of the initial, e.g. from 0.6 to 0.43). There was also a slight decrease in VA in the earlier operated pseudophakic fellow eyes. This decrease of 0.07 logMAR could be due to incipient secondary cataract. An analysis of reasons for this change was not conducted in this study.

Car driving requires VA ≥0.5. One indication for cataract surgery is to a maintain driver's licence. In Study I 66% of patients initially had VA ≥0.5 in the better eye. Preoperatively, the number of these patients had fallen to 41%. If the situation was similar throughout the country, this means that according to 1994 statistics there were at least 1000 patients who had lost the vision level required for driving while waiting for the operation.

At the time of referral, 10 patients (8%) could be classified as visually handicapped (VA of the better eye <0.3), but prior to surgery their number had increased to 26 (21%).

Possibly, other ocular diseases in the operated eye could have worsened VA. However,of the operated eyes, 88 (71%) had no ocular diagnosis besides cataract. Five patients had diabetes without significant retinopathy and five had macular degeneration. Other ocular diseases were glaucoma in 12% of the operated eyes, corneal opacities in five eyes and other diseases in seven eyes, all of which had likely stayed stable during the waiting period. Consequently, the progression of cataract was the main factor responsible for the worsening of vision in these eyes.

The great variation in changing speeds in VA in cataractous eyes and the certain imprecision of VA measurement should indicate remeasurement of VA in borderline cases before referral to operation, and in hospitals with long waiting lists, the patients ought to be followed regularly.

6.2 Waiting time in relation to expected life span

The mean waiting time, 13 months, from referral to surgery in Study I was 13% of the expected mean lifetime of patients. Older patients lost a larger proportion of their remaining years. This could be a reason to give older patients priority for the operation, although results of cataract extraction on older patients are more often unsatisfactory (Lumme & Laatikainen 1993). On the other hand, for younger patients, surgery may help to preserve or restore working capacity. Altogether, about 85% of cataract patients get help from cataract extraction (Lumme 1994, Stenevi et al. 1995). The time spent in waiting means losing the possibility for visual improvement during this period. The life statistics used here were based on the total population in Finland. Morbidity of patients and cataract patients, especially younger patients, having a shorter life expectancy (Benson et al. 1988, Street & Javitt 1992) were not taken into account. If cataract patients die younger than the rest of the population, the time spent on the waiting list could be even greater in relation to the expected survival after cataract surgery.

Today, the waiting time for cataract surgery in Finland is shorter; in 2003, the mean waiting time was 8.1 months (Stakes Report 2005), and at the end of 2005, a total of 10 797 patients waited for cataract extraction (Punnonen 2006), which is about 28% of the annual number of these operations in Finland. Thus, average waiting time has decreased to about three to four months.

6.3 Estimate of costs of the waiting time for patients

Waiting for operation means losing the possibility for vision improvement during this period. About 37 100 cataract extractions were performed in community-based hospitals in Finland in 2003 (which is 90% of all extractions) (Stakes Report 2005). The average waiting time in the whole country was 8.1 months (Stakes Report 2005). This means a total of 25 000 patient-years for a total of 37 100 patients. The average life expectancy for patients (both sexes) in Study I was 9.5 years. Thus, the waiting time meant a loss of benefit produced by about 2600 cataract extractions per year when calculated as benefit for 9.5 years. This corresponds to the production of cataract extractions in a greater size ophthalmic unit in Finland.

6.4 Increase of incidence of cataract extractions

At the beginning of the 1980s, the technique used for cataract extraction was predominantly intracapsular, and no intraocular lenses were implanted. The extracapsular technique (ECCE) with intraocular lens implantation was brought to wider use in the middle of the 1980s. Intraocular lenses were inserted without bending the lens through a wound which was more than 7 mm wide because expulsion of the nucleus. At the beginning of the 1990s, the phakoemulsification technique was adopted. This meant that a bended lens could be placed through a 3-mm corneoscleral or corneal wound into the capsular bag. The results of surgery improved, and the patients' willingness to have the operation increased. Today's society also has a higher demand for good vision; with many cataract patients having a driver's license, product declarations in grocery stores being written in small text and a vast majority of people engaged in TV watching. Thus, admittance to operation has increased dramatically, resulting in a lengthening of waiting times. At the beginning of 1980s the waiting time for cataract surgery was usually less than 6 months, while in 2000, the typical waiting time for cataract extraction in Finland was more than one year.

Finnish National Research and Development Centre for Welfare and Health statistics (Stakes 2000) reveal cataract as the main diagnosis in 5 335 hospital admissions in 1982. Thus, the incidence of cataract surgery in Finland in 1982 was 1.1 operations per 1000 inhabitants. In 2000, the number of cataract operations was about 35 000 (Stakes Report 2005). However, the number in 2000 was probably even greater because the statistics do not cover some private clinics. The number of cataract operations had thus increased to about sevenfold in 2000, and the incidence per 1000 inhabitants to 6.7. The rise continued in 2005, when 38 216 cataract extractions, 9% of which were binocular and included a total of 41 657 operated eyes, were performed in community-based hospitals (Punnonen 2006). If the private sector is assumed to perform 4000 extractions, the annual rate of cataract extractions in Finland was 8.1 per 1000 inhabitants in 2005. The figures have undoubtedly risen because of the new law (856/2004), stating that elective surgery in community-based health care must be provided within 6 months. In Sweden, the incidence in 1999 was 6.79 (Lundström et al. 2001b). Foster (2001) calculated incidences of 4.0 per 1000 inhabitants in Western Europe and 5.5 per 1000 inhabitants in North America.

The number of operations performed in the Vaasa Central Hospital district increased over the years covered in this study (II) from 159 in 1982 to about 1200 in 2000. Because few individuals had undergone cataract operation outside the region, these figures can be assumed to provide reasonably reliable information about the incidence of cataract surgery for the region. Incidences calculated for Vaasa were similar to those for the whole country, 1.0 per 1000 inhabitants in 1982 and 7.2 per 1000 inhabitants in 2000.

One reason for the increasing incidence of cataract surgery is the rising number of elderly individuals. From 1982 to 2000, the population of Finland increased from 4.8 million to 5.2 million, i.e. by 8%. Over the same period, the number of inhabitants aged 65 or over increased from 600 000 to about 780 000, i.e. by 30% (Statistical Yearbook of Finland 2001). The population in the Vaasa district simultaneously increased by 1.2%, and the number of individuals aged over 63 years increased from 24 500 in 1982 to 30 200 in 2000 (22.5%). The increase in numbers of the elderly could therefore explain only about 1600 (5%) of the increase of 30 000 operations in the country between 1982 and 2000. Thus, the change in the age distribution of the population can account for only a small proportion of the increase in cataract operations in the whole country and in the Vaasa region. The main explanation for the increased incidence is the change in indications for cataract surgery.

The number of cataract operations has been estimated to increase 2.5-fold if the indication for surgery changes from VA <0.1 to <0.25, 5-fold if the change is to <0.5 (Taylor 2000, Foster 2001). A change in indication from VA <0.1 to <0.25 is equal to 4 log lines, and a change from <0.1 to <0.5 is equal to 7 log lines. These estimates are in accordance with the present findings that an increase of one operation per year per 1000 inhabitants corresponded to an average improvement in VA of 1.3 log lines. The average improvement of VA in the better eye had been less, 0.4 log lines per one operation increase per 1000 inhabitants. Corresponding decimal values for VA before surgery in the operated eye were 0.03 (1.0 operation per 1000 inhabitants in 1982) and 0.2 (7.2 operations per 1000 inhabitants in 2000). In the better eye, the values were 0.23 and 0.43, respectively.

The percentage of individuals profoundly visually handicapped (VA of better eye <0.1) before the operation fell from 14.8 in 1982 to 3.7 in 2000. The proportion of moderately visually handicapped individuals (VA of the better eye < 0.3) in 2000 was only about one third (11.1%) of that in 1982 (32.1%). In Study I, the corresponding figure was 21%. VA below 0.5 was described as "economic blindness" by Taylor & Keeffe (2001) because a VA of 0.5 or more is usually needed to hold a driving licence. The percentage of patients with a VA of at least 0.5 in their better eye increased in Study II from 33 in 1982 to 48 in 2000. However, the proportion of individuals with a VA of less than 0.5 in their better eye was still as high as 52% in 2000 (Study II) and 59% in 1997 (Study I). In a European study of the outcome of cataract surgery in which 31 surgical units in 13 countries participated in 1998, the percentage of "economic blindness" was lower. VA was less than 0.5 in only 36% of the nonsurgical (fellow) eyes (Lundström et al. 2001a). There was, however, substantial variation in percentages (from 13 to 67) between units, probably because of great variation in incidence of second-eye surgery.

The incidence of second-eye cataract surgery has increased markedly (Bernth-Petersen 1981, Javitt et al. 1995, Castells et al. 2000). In the present series (Study II), it had increased from 15% in 1982 to 36% in 2000. The latter finding is in accordance with the poportion (37%) reported by Lundström et al. (2001b) for Sweden in 1999. In the European cataract outcome study, the average frequency of second-eye surgery was 42% (range 17–77%) (Lundström et al. 2001a).

The percentage of individuals who had been suffering from ocular disease other than cataract was similar to that in the European Cataract Outcome Study

(Lundström et al. 2001a). Ocular comorbidity had not altered significantly between 1982 and 2000. In 2000, a slightly greater proportion of patients (83%) had been suffering from general disease than in the previous years, perhaps because the average age of patients in 2000 was marginally higher than in previous years. In addition, fewer diseases are now regarded as contraindications to operative treatment since operation times and stays in hospital have become shorter.

In conclusion, the mean preoperative VA has increased from 1.56 logMAR to 0.71 logMAR, i.e. 0.85 logMAR units or 8.5 log lines, between the years 1982 and 2000. The corresponding Snellen decimal values are 0.03 for 1982 and 0.2 for 2000. At the same time, the cataract surgery rate has increased from 1.0 to 7.2 operations per 1000 inhabitants per year. Earlier operative intervention in cataract treatment has considerably diminished the number of people who are visually handicapped by cataract.

6.5 Repeatability of visual acuity measurements

The purpose of this work was to study one important parameter of vision, visual acuity, in clinical conditions. VA is apparently the most important single measure of vision on which clinical decisions of ophthalmic patients are based. VA does not express all qualities of vision, but compared with many ophthalmic examinations, it is reasonably precise, easily available and easy to perform. This is probably why legislation is mainly based on results of VA.

In clinical work, many factors may cause inaccuracy in measurement. This inaccuracy may decrease reliability in ophthalmic patient's management and affect granting of driver's licences and allocation of support for the visually handicapped. In patients of this study, VA was mainly lowered by cataract. To measure VA, the best refractive correction must also be measured. REM is also subject to inaccuracies. Inaccuracy in REM might increase the inaccuracy of the VA result.

The accuracy of VA measurement is known to be worse in clinical conditions than in controlled laboratory settings, the latter usually entailing measurements on healthy eyes with good vision. In this study, the reliability of decisions concerning changes in VA in patients with lowered vision was investigated. REM is tightly bound to VA measurement when determining BCVA. This measurement, too, is a psychophysical test with a tendency to produce variable results, and therefore, REM repeatability also was evaluated.

Previous studies investigating repeatability of VA are summarized in Table 14. In most studies, repeatability varies between ±0.08 logMAR and ±0.33 logMAR. The differences may be partly due to different patient samples and different VA acuity charts. In the present study, repeatability was within these limits: in eyes with good VA (>0.7), repeatability, CR, was ±0.12 logMAR and in eyes with lower VA (0.3–0.45) ±0.24 logMAR. An earlier study (Gibson & Sanderson

1980) on cataractous eyes (VA of 6/9 or worse) found a difference of 2 lines or more in 13% of cases, which is somewhat more than in the present study (3/41 eyes, 7%). CR for all eyes was 0.18 logMAR, and standard deviation for the measurement error (SDME) was 0.064 logMAR. SDME varied in different vision groups from 0.04 to 0.09 logMAR.

Table 14. Results of studies investigating repeatability of visual acuity measurements

	Patients, examination site	Repeatability (95% limits of agreement), logMAR	Visual acuity charts
Arditi & Caganello 1993	5 highly practised normal subjects, laboratory conditions	± 0.1	Sloan letters, 5/line, 0.1 logMAR line size progression
Gibson & Sanderson 1980	Clinical outpatients, cataractous eyes, VA <6/9, nurses examined, n 64	13% of measurements differed by 2 lines or more	Illuminated Snellen charts
Raasch et al. 1998	Literature review, 4 studies, 1976–1998	± 0.08 – 0.12	Sloan letters, 5/line, 0.1 logMAR line size progression
Rosser et al. 2001	Clinical outpatients with eye diseases, VA 0.1–1.2, n 41	± 0.33 ± 0.24	Snellen, line assignment Single letter assignment
Siderov & Tiu 1999	Clinic patients, VA ≥0.1, aged 18 to 75, n=50	± 0.15	Varying VA charts
Van den Brom et al. 1995	Cataract patients, mean VA 0.23 logMAR (Snellen 0.6), n 50	± 0.08	ETDRS and Landolt-C TNO
Elliott & Sheridan 1988	Cataract patients, n 15, eyes 29.	± 0.09	ETDRS
Study III	Clinic patients, cataractous, pseudophakic and healthy eyes. VA ≥0.3, aged 26–89, n 99	Row-by-row scoring/ partly read lines ± 0.18, all ± 0.12,VA >0.7 ± 0.24 ,VA 0.3–0.45	Different charts, environments and clinicians

Variability in this study was less than that found by Rosser et al. (2001), but VAs were better, ranging from 0.3 to normal. In Rosser's study, the ETDRS chart was taken as a gold standard. The variability observed our study was fairly similar to that reported by Siderov and Tiu (1999) for healthy eyes, but greater than that reported by Elliott and Sheridan (1988) and van den Brom et al. (1995) for cataractous eyes.

To our knowledge,the dependence of VA on the REM error, in routine clinical practice, has not been previously investigated. In most cases, we obtained different results in REM 1 and 2. At least one of these must therefore be incorrect. Not knowing the real value, the best estimate is the midvalue (average) between the two (Bland 1988). To elucidate the effect of incorrect refraction on VA, we used defocus equivalents (DEs) as described by Holladay et al. (1991). DE describes in diopters how far the obtained test-retest values (REM 1 and 2) are from each other. The difference between REM 1 and 2 as vector values was calculated, converted back to traditional notation, from which DE can be calculated as the sum of the absolute value of SE and half a cylinder, according to Holladay et al. (1991). In empirical studies, quite a large variation exists for depth of field for a given pupil size: 0.6–1.3D for a 2-mm pupil, 0.4D-1.2 D for 5-mm pupil (Ciuffreda 1998). It is reasonable to assume that the depth of field in the eyes at our study would be in this range, which is one factor that can give visual tolerance to refractive miscorrections. In accommodating eyes, the measurement error can partly be compensated by accommodation. The expected value of true refractive error is the mean of REM 1 and 2. Thus, in eyes without accommodation potential, the expected average decrease was 0.04 logMAR (Table 12), suggesting that VAs could have been a little less than half a line better with exact corrections. For the reasons given above, i.e.depth of field and accommodative compensation, the expected average decrease could be even less. This is not much when compared with CR 0.18 logMAR (SD 0.09 logMAR). The maximum value (Table 12) is the VA decrease with the assumption of the greatest REM difference with one REM value being correct and the other incorrect with the quantity of total difference. The VA decrease is for the latter. This situation is, of course, quite unlikely. Most of the time, REM differences as DEs were < 0.5D (Table 11).

The variability of VA determination increases when the size progression between lines increases and when there are fewer optotypes per line (Raasch et al. 1998; Vanden Bosch & Wall 1997). In the present study, there were six different projectors. The VA (in the first examination) varied between 0.3 and 1.3 (0.52 logMAR to –0.11 logMAR), and in the VA charts the mean difference between lines was 0.088 logMAR (range 0.046 to 0.125). The mean size progression was thus smaller than in the ETDRS charts (0.1 logMAR). The largest size difference (0.125) was in most cases between lines 0.3 and 0.4, and line 0.3 contained only a the mean of 3.8 optotypes per line. Thus, one letter had an average value of 0.031 logMAR compared with 0.02 in the ETDRS chart. The average VA value per letter in the vision range studied was 0.022, which is close to 0.02 in the ETDRS chart. Because VAs were recorded only as correctly or partly correctly read lines, there were only two values per line having an average of 0.044 logMAR unit per line. The measurement error thus increases by a factor of $(0.044/0.02)^{1/2}$ =1.48 as compared with the ETDRS chart read letter by letter (Bailey 1998). In the ETDRS chart, the total number of correctly read letters gives the logMAR score. The same principle could also be used with other clinical charts without any great difficulties, although the number of letters varies between lines.

Some of the examinations in this study were made reading numbers instead of letters. The recognizability of numbers, like that of letters, varies. However, the affect of readability of letters has only a small influence on measurement error in VA measurement (Raasch et al. 1998). Sloan letters give slightly better acuities than British Standard letters (0.033 logMAR) (Raasch et al. 1998). In the present study, British Standard letter charts and Sloan letter charts were fairly evenly distributed, and therefore, probably did not cause any systematic measurement error.

The variability estimated in the present study was small considering that the charts were not ideal as compared with ETDRS charts. Estimates of variability of VA determination may vary considerably among sites depending on clinical procedure. The outcome of the present study is in accordance with previous studies. VAs were somewhat better in the second examination than in the first, especially in poorly seeing eyes. In previous studies, the difference between the first and second examinations has usually been insignificant (Klein et al. 1983, Elliott & Sheridan 1988, Siderov & Tiu 1999, Rosser et al. 2001). Few studies have been performed on cataractous or pseudophakic eyes. If examinations were conducted within 75 days, there was a greater difference than if the time interval between examinations was longer. The difference could mean that patients exhibit some learning in VA testing. Other possibilities include more vigorous VA testing during later examination or patient psychological factors. These factors could be a reality in clinical work systematically altering results slightly. Because of the rough "half line" assignment used, one might think that the variability was not normally distributed, but that was not the case.

One-fourth of the measurements in the visual VA group of 0.3–0.65 were on different sides of the VA value of 0.5 required for a driver's licence in Finland. The result is actually not very surprising. If we get a result of VA 0.5, for a repeated measurement 95% CI is 0.5 ±0.24 logMAR (Table 9) which is equivalent to Snellen 0.3–0.8. Both random errors and systematic errors, such as learning, may have an influence on the incorrect classification for car driving capability or visual handicap. A single testing of VA when considering cataract extraction can also be misleading. Especially in borderline cases, visual complaints are a more important consideration as an indication for surgery (Gibson & Sanderson 1980, Monestam & Wachtmeister 1998, Uusitalo et al. 1999, Pager et al. 2004).

In the poorly seeing group (VA 0.3–0.45), the CR was 0.24 logMAR, which means that for a change in VA in a single case the SDME for change is √2*0.24 logMAR, or 0.34 logMAR or 3.4 log lines (Bland 1988, Bailey 1998). For a group of 10 individuals in this VA group, we obtained 0.34/√10 = 0.11 logMAR 95% CI for change. For the VA ≥0.7 group, the CR was 0.12 logMAR and the change in VA in a single case is 0.17 logMAR (95% CI).

Charts with a logarithmic progression of lines would increase the precision of VA measurements in clinical work. The lack of this did not, however, have a great influence on the results in the visual groups studied. More variation would likely have occurred had lower acuity groups been measured.

6.6 Repeatability of refractive error measurement

Investigations measuring repeatability of subjective REM are rare, and most have been conducted on healthy eyes. Zadnik et al. (1992) reported the subjective refraction repeatability of the sphere to be 0.063 ±0.63 D (95% CI). In most of the reviewed studies, the intraexaminer and interexaminer reliability of subjective refraction were close to 80% agreement within ±0.25 D and 95% agreement within ±0.5 D for spherical equivalent, spherical power and cylinder power (Goss & Grosvenor 1996).

We obtained a similar spherical equivalent, CR ±0.51D in the best VA group (≥0.7), but in the lowest VA group there was more variability, CR ±1.14D (68% of differences in REM 1 and 2 within ±0.5D limits); the difference in variability was not, however, statistically significant. The best VA group corresponds to the results reported in a review on papers that had studied repeatability of conventional and autorefraction (Goss & Grosvenor 1996) and to the findings of Zadnik et al. (1992).

Elliott et al. (1997) used vector calculations in measuring repeatability of subjective refraction in healthy eyes with VA a of 6/6 or better. They defined CR as vertical (V), torsional (T) and horizontal (H) variability. CR of subjective refraction was 0.611D (V), 0.224D (T) and 0.490D (H). The torsional component was equivalent, with 1D cylinder axis variability of ±9.2°.

In the present study, repeatability (CR) for vertical (V), torsional (T) and horizontal (H) vectors for all eyes was 0.74D, 0.34D and 0.93D, respectively, which is worse than reported by Elliott et al. (1997) in healthy eyes, but in the VA group of ≥0.7 the CR values of the vector components (0.57D, 0.32D and 0.71D) are closer to those of Elliott et al. (1997). Because V and H vectors together describe variation of the spherical component (Harris 1990a), this component varied more than the cylindrical component.

Defocus equivalent as calculated from the difference between REM 1 and 2 can be used as an estimate of REM error influence on VA. In the group VA ≥0.7, the average DE (for difference in REM 1 and 2) was 0.40 D, and in the poorly seeing group of VA 0.3–0.45 the average DE was 0.71 D. The difference between the groups is significant and shows that sensitivity to dioptral changes decreases with lower VA. Our observations measured as DEs are in accordance with the results of Legge et al. (1987).

The maximum values of DE were also quite uniform. It is not exluded that maximum values for DE might be even greater. This is the case when the true value of refractive error is outside the range from REM 1 to REM 2 (both of the obtained REM values are too small or too large). In most cases, this was very unlikely because standard deviation was uniformly small, of the magnitude of 0.04 logMAR. Part of logMAR values can also be smaller, at least for distance VA, because some eyes could compensate by accommodation. Large DE values were also quite uncommon (Table 11); the total number of eyes exceeding DE for difference of 0.5D was 7/99 (7%). Only 2/59 eyes in the VA group of ≥0.7 had DE >0.5D, and in 10/59 eyes (17%) DE was ≥0.3D.

Despite several testers and varying clinical test conditions, the variability in REM was fairly small. As a consequence, REM in these visual categories (VA 0.3–1.3) is reasonably reliable. However, the precision of REM seems to decrease with decreasing VA. Thus, conclusions concerning changes in the refractive state and decisions to make changes in spectacle correction have to be more conservative when dealing with lower vision eyes. If we accept a change of 0.5D (measured in DEs) as a basis for change of spectacles for well-seeing eyes, the basis for poorly seeing eyes should be almost double, 1.0D.

7. Conclusions

Cataract extraction rates in Finland increased about sevenfold from 1982 to 2000. This led to a lengthening of waiting time for surgery. During the long waiting time, many patients experienced a decrease in VA. There was, however, a wide variation in this decrease. About half of the patients had no essential worsening in vision during the 13-month waiting period, one-fourth had a decrease of almost three log lines per year and one-fourth had a marked decrease of 7 to 8 log lines per year.

The waiting time for operation comprised a considerable proportion of the patients' life expectancy and meant a loss of benefit from cataract extraction for this period.

From 1982 to 2000, the cataract surgery rate increased from 1.0 to 7.2 operations per 1000 inhabitants per year. As a consequence of greatly increased cataract extraction rates, VAs in both operated eyes and better eyes rose markedly, more in the operated eyes. Fewer patients entered cataract extraction as visually handicapped. Preoperative VA increased linearly with incidence of operation. Only a small proportion of the increase in incidence of cataract surgery can be explained by increasing age of the population.

VA and REM are psychophysical measurements that especially in clinical settings, have a variety of factors that contribute to imprecision and perhaps also to inaccuracy. Standard deviation of measurement error in eyes with good VA was slightly less than half a log line, in worse seeing eyes almost a line. Repeatability, as expressed in CR, was with good VA about one log line and with lower VA more than two lines. This means a risk of misclassification when dealing with cases close to the legal limit for e.g.car driving or classifying a patient as visually handicapped. To be confident of a change in VA in well-seeing eyes, the change has to be more than one log line and for VA groups 0.3–0.65 more than two lines. In the lower VA groups in our study, the mean of measured paired acuities was slightly better in the second examination than in the first suggesting that some learning effect takes place.

In REM repeatability was lower in spherical than cylindrical values. CR expressed in SEs, was ±0.5D in eyes with good VA and ±1.1D in VA group 0.3–0.45. If the need for change of spectacles is regarded as DE ±0.5D, in the lower VA group it should therefore be ±1D. The mean of test and retest values was very close to zero, indicating that refractive errors were measured without systematic error.

In clinical situations, BCVA is dependent on REM, which also contained imprecision. This imprecision gives lower VA values than would have been reached had the correction been ideal. In our study, this effect was estimated to be 0.04 logMAR or less. Thus, the major factor resulting variability in VA measurements is the measurement of VA itself.

8 References

Arditi A, Caganello R. On the statistical reliability of letter chart visual acuity measurements. Invest Ophthalmol' Vis Sci 1993;34:120–129.

Bailey IL. Visual acuity. In: Benjamin WJ (ed.). Borish's Clinical Refraction. Philadelphia. W.B. Saunders Company 1998;179–201.

Beebe DC. The lens. In: Adler's Physiology of the Eye. Mosby. St. Louis, Missouri 2003; 115–158.

Bennett AG, Rabbetts RB. Visual acuity. In: Clinical Visual Optics. Butterworths, London 1984a;21–57.

Bennett AG, Rabbetts RB. Ocular aberrations and inadequate-stimulus myopias. In: Clinical Visual Optics. Butterworths, London 1984b;291–321.

Bennett AG, Rabbetts RB. Spherical ametropia. In: Clinical Visual Optics. Butterworths, London 1984c;59–77.

Bennett AG, Rabbetts RB. Astigmatism. In: Clinical Visual Optics. Butterworths, London 1984d;79–94.

Bennett AG, Rabbetts RB. Subjective refraction. In: Clinical Visual Optics. Butterworths, London 1984e;95–117.

Benson WH, Farber ME, Caplan RJ: Increased mortality rates after cataract surgery. A statistical analysis. Ophthalmology 1988;95:1288–1292.

Bergman B, Nilsson-Ehle H, Sjöstrand J. Ocular changes, risk markers for eye disorders and effects of cataract surgery in elderly people: a astudy of an urban Swedish population followed from 70 to 97 years of age. Acta Ophthalmol Scand 2004;82:166–174.

Bernth-Petersen P. A change in indications for cataract surgery? A 10 year comparative epidemiologic study. Acta Ophthalmol (Copenh) 1981;59:206–10.

Bland M, Altman D. Statistical methods for assessing agreement between two methods of clinical measurement. The Lancet 1986;8:307–310.

Bland M. Clinical Measurement. In: An Introduction to Medical Statistics. Oxford University Press 1988;276–283.

Borish IM, Benjamin WJ. Monocular and binocular subjective refraction. In: Borish's Clinical Refraction. W.B. Saunders Co, Philadelphia 1998;629–723.

Broman AT, Munoz B, Rodriguez J, Sanchez R, Quigley HA, Klein R, Snyder R, West SK. The impact of visual impairment and eye disease on vision-related quality of life in a Mexican-American population: Proyecto VER. Invest Ophthalmol Vis Sci. 2002;43:3393–3398.

Cairns L, Sommer A. Changing indications for cataract surgery. Trans Am Ophthalmol Soc 1984;82:166–175.

Camparini M, Cassinari P, Ferrigno L, Macaluso C. ETDRS-fast: implementing psychophysical adaptive methods to standardized visual acuity measurement with ETDRS charts. Invest Ophthalmol Vis Sci. 2001;42:1226–1231.

Campbell CE, Benjamin WJ, Howland HC. Objective refraction: retinoscopy, autorefraction, and photorefraction. In: Benjamin WJ (ed.). Borish's Clinical Refraction. Philadelphia: W.B. Saunders Company 1998;559–628.

Castells X, Alonso J, Ribo C, Nara D, Teixido A, Castilla M. Factors associated with second eye cataract surgery. Br J Ophthalmol 2000;84:9–12.

Central Bureau of Statistics (Finland) (1995). Vital Statistics 1994.

Ciuffreda KJ.Accommodation, the pupil, and presbyopia. In: Benjamin WJ (ed.). Borish's Clinical Refraction. W.B. Saunders Company, Philadelphia;1998:98–101.

Cravy TV. Calculation of the change in corneal astigmatism following cataract extraction. Ophthalmic Surg. 1979;10:38–49.

Desai P, Reidy A, Minassian DC, Vafidis G, Bolger J. Gains from cataract surgery: visual function and quality of life. Br J Ophthalmol 1996;80:868–873.

Desai P, Reidy A. Minassian DC. Profile of patients presenting for cataract surgery in the UK: national data collection. Br J Ophthalmol. 1999;83:893–896.

Elliott DB, Bullimore MA, Patla AE, Whitaker D. Effect of a cataract simulation on clinicat and real world vision. Br J Ophthalmol 1996; 80:799–804.

Elliott DB, Gilchrist J, Whitaker D. Contrast sensitivity and glare sensitivity changes with three types of cataract morphlogy: are these techniques necessary in a clinical evalution of cataract? Ophthalmic Physiol Opt. 1989;9:25–30.

Elliott DB, Sheridan M. The use of accurate visual measurements in clinical anticataract formulation trials. Ophthalmic Physiol Opt 1988;8:397–401.

Elliott DB, Situ P. Visual acuity versus letter contrast sensitivity in early cataract. Vision Res 1998;38:2047–2052.

Elliott DB, Yang KCH, Whitaker D. Visual acuity changes in normal healthy eyes. Seeing beyond 6/6. Optom Vis Sci 1995;72:186–191.

Elliott M, Simpson T, Richter D, Fonn D. Repeatability and accuracy of automated refraction: A comparison of the Nikon NRK-8000, the Nidek AR-1000, and subjective refraction. Optom Vis Sci 1997;74:434–438.

Espallargues M, Alonso J. Effectiveness of cataract surgery in Barcelona, Spain. Site results of an international study. Barcelona I-Port investigators. International Patient Outcomes Research Team. J Clin Epidemiol 1998;51:843–852.

Fletcher A, Vijaykumar V, Selvaraj S, Thulasiraj RD, Ellwein LB. The Madurai Intraocular Lens Study.III: Visual functioning and quality of life outcomes. Am J Ophthalmol 1998;125:26–35.

Foster A. Cataract and "Vision 2020 – the right to sight" initiative. Editorial. Br J Ophthalmol 2001;85: 635–639.

Gibson RA, Sanderson HF. Observer variation in ophthalmology. Br J Ophthalmol 1980;64:457–460.

Glasser A, Kaufman PL. Accommodation and presbyopia. In: Adler's Physiology of the Eye. Mosby, St. Louis, Missouri. 2003;195–233.

Goss DA, Grosvenor T. Reliability of refraction – a literature review. J Am Optom Assoc 1996;67:619–630.

Guzowski M, Wang JJ, Rochtchina E, Rose KA, Mitchell P. Five-year refractive changes in an older populaion: the Blue Mountains Eye Study. Ophthalmology 2003;110:1364–1370.

Hamam H. Aberrations and their impact on image quality. In: Wavefront Analysis, Aberrometers and Corneal Topography. Highlights of Ophthalmology International. El Dorado Panama Rep. of Panama 2003;189–216.

Harris WF. The mean and variance of samples of diopric powers: the basic calculations. Clin Exp Optom 1990a;73:89–92.

Harris WF. Statistical inference on mean dioptric power: hypothesis testing and confidence regions. Ophthal Physiol Opt 1990b;10:363–372.

Harris WF. Direct, vec and other squares, and sample variance-covariance of dioptric power. Ophthal Physiol Opt 1990c;10:72–80.

Harris WF:Astigmatism. Ophthal Physiol Opt. 2000;20:11–30.

Harwerth RS, Schor CM. Binocular Vision. In: Adler's Physiology of the Eye. Mosby, St. Louis, Missouri 2003;484–510.

Holladay JT, Cravy TV, Koch DD. Calculating surgically induced refractive change following ocular surgery. J Cataract Refract Surg 1992;18:429–443.

Holladay JT, Dudeja TR, Koch DD. Evaluating and reporting astigmatism for individual and aggregate data. J Cataract Refract Surg 1998;24:57–65.

Holladay JT, Lynn M, Waring GO III, Gemmill M, Keehn GC, Brooke F. The relationship of visual acuity, refractive error, and pupil size after radial keratotomy. Arch Ophthalmol 1991;109:70–76.

Holladay JT, Prager C. Mean visual acuity (letter). Am J Ophthalmol 1991;111:372–374.

Holladay. Proper method for calculating average visual acuity. Journal of Refractive Surgery 1997;13: 388–91.

Ijspeert JK, de Waard PW, van den Berg TJ, de Jong PT. The intraocular straylight function in 129 healthy volunteers; dependence on angle, age and pigmentation. Vision Res 1990;30:699–707.

Javitt JC, Steinberg EP, Sharkey P, Schein OD, Tielsch JM, West MD, Legro M, Sommer. A Cataract surgery in one eye or both. Ophthalmology 1995;102:1583–1593.

Jay JL, Devlin ML. The increasing frequency of surgery for cataract. Eye 1990;4:127–31.

Jayamanne DG, Allen ED, Wood CM, Currie S. Correlation between early, measurable improvement in quality of life and speed of visual rehabilitation after phacoemulsification. J Cataract Refract Surg 1999;25:1135–1139.

Johnson BL, Edwards JS, Goss DA, Penisten DK, Fulk GW. A comparison of three subjective tests for astigmatism and their interexaminer reliabilities. J Am Optom Assoc 1996;67:590–597.

Kaye SB, Harris WF. Analyzing refractive data. J Cataract Refract Surg 2002;28:2109–2116.

Keating MP. A system matrix for astigmatic optical systems: I.Introduction and dioptric power relations. Am J Optom Physiol Opt. 1981;58:810–819.
Keating MP. An easier method to obtain the sphere, cylinder, and axis from an off-axis dioptric power matrix. Am J Optom Physiol Opt 1980;57:734–737.
Keating MP. Dioptric power in an off-axis meridian: the torsional component. Am J Optom Physiol Opt 1986;63:830–838.
Klein R, Klein BE, Moss SE, DeMets D. Inter-observer variation in refraction and visual acuity measurement using a standardized protocol. Ophthalmology 1983;90:1357–1359.
Legge GE, Mullen KT, Woo GC, Campbell FW. Tolerance to visual defocus. J Opt Soc Am Assoc 1987;4:851–863.
Leske MC, Chylack LT, Qimei He, Suh-Yuh Wu, Schoenfeld E, Friend J,Wolfe J, The LSC Group. Incidence and progression of cortical and posterior subcapsular opacities. The Longitudinal Study of Cataract. Ophthalmology 1997;104:1987–1993.
Leske MC, Chylack LT, Suh-Yuh Wu, Schoenfeld E, Qimei He, Friend J,Wolfe J. The Longitudinal Study of Cataract Group. Incidence and progression of nuclear opacities in the Longitudinal Study of Cataract. Ophthalmology 1996;103:705–712.
Long WF. A matrix formalism for decentration problems. Am J Opt Physiol Opt 1976;53:27–33.
Lumme P, Laatikainen L. Factors affecting the visual outcome after cataract surgery. Int Ophthalmol 1993;17:313–319.
Lumme P. Cataract Surgery : Sociodemografic aspects and general health of patients, risk factors for complications and short–term visual outcome 1994. Academic dissertation. University of Oulu.
Lundström M, Barry P, Leite E, Seward H, Stenevi U a. 1998 European Cataract Outcome Study. Report from the European cataract outcome study group. J Cataract Refract Surg 2001;27:1176–1184.
Lundström M, Stenevi U, Thorburn W b. Age-related utilisation of cataract surgery in Sweden during 1992–1999. A retrospective study of cataract surgery rate in one-year age groups based on the Swedish National Cataract Register. Acta Ophthalmol Scand. 2001;79:342–349.
Lundström M, Stenevi U, Thorburn W. Gender and cataract surgery in Sweden 1992–1997. Acta Ophthalmol Scand. 1999;77:204–208.
Lundstrom M, Stenevi U, ThorburnW. The Swedish National Cataract Register: A nine year review. Acta Ophthalmol 2002;80:248–257.
Magno BV, Datiles MB, Lasa SM. Progression of lens opacities in cataract patients after one year. Acta Ophthalmol Scand. 1995;73:45–49.
Magno BV, Datiles MB, Lasa SM. Senile cataract progression studies using the Lens Opacities Classification System II. Invest Ophthalmol Vis Sci 1993;34:2138–2141.

McCarty CA, Mukesh BN, Dimitrov PN, Taylor HR. Incidence and progression of cataract in Melbourne Visual impairment project. Am J Ophthalmol 2003;136:10–17.

McGraw PV, Winn B, Gray LS, Elliott DB. Improving the reliability of visual acuity measures in young children. Ophthalmic Physiol Opt 2000;20:173–184.

McGwin G, Scilley K, Brown J, Owsley C: Impact of cataract surgery on self-reported visual difficulties. Comparison with a no-surgery reference group. J Cataract Refract Surg 2003;29:941–948.

MedCalc Manual. MedCalc for Windows 8.1 Manual. 2005. URL http://www.medcalc.be/manual

Michaels David. Visual acuity. In: Visual Optics and Refraction, a Clinical Approach. Saint Louis: Mosby 1975a;170–180.

Michaels David. Optical principles in the correction of ametropia. In: Visual Optics and Refraction, a Clinical Approach. Saint Louis: Mosby 1975b;109–130.

Michaels David. Cylindrical lenses. In: Visual Optics and Refraction, a Clinical Approach. Saint Louis: Mosby 1975c;54–67.

Michaels David. Clinical retinoscopy. Subjective methods of refraction. In: Visual Optics and Refraction, a Clinical Approach. Saint Louis: Mosby 1975d;212–241.

Miller D. Physiologic optics and refraction. In: Adler's Physiology of the Eye. Mosby, St. Louis, Missouri: 2003;161–194.

Monestam E, Wachtmeister L. Cataract surgery from a gender perspective – a population based study in Sweden. Acta Ophthalmol Scand. 1998;76:711–716.

Monestam E, Wachtmeister L. Change of subjective visual function in the first-eye cataract patients when the rate increases in the population. Medical care 2002;40:1080–1089.

Monestam E, Wachtmeister L. Impact of cataract surgery on visual actuity and subjective functional outcomes: a population-based study in Sweden. Eye 1999;13:711–719.

Montes-Mico R, Alio JL, Munoz G, Charman WN. Temporal changes in optical quality of air-tear film interface at anterior cornea after blink. Invest Ophthalmol Vis Sci 2004;45:1752–1757.

Moorman C, Sommer A, Stark W, Enger C, Payne J, Maumenee AE. Changing indications for cataract surgery: 1974 to 1988. Ophthalmic Surg 1990;21:761–766.

Naeser K. A new method to describe the surgically induced change in corneal astigmatism. Acta ophthalmol (suppl. 195) 1990;68:33–36.

Naeser K. Assessment of surgically induced astigmatism; call for an international standard. J Cataract Refract Surg 1997;23:1278–1280.

National Research and Development Centre for Welfare and Health (Finland) (1996a): Statistical Report: 1995:37.

Neumann AC, McCarty GR, Steedle TO, Sanders DR, Raanan MG. The relationship between indoor and outdoor Snellen visual acuity in cataract patients. J Cataract Refract Surg. 1988;14:35–39.

Norregaard JC, Bernth-Petersen P, Alonso J, Dunn E, Black C, Andersen TF, Espallargues M, Bellan L, Anderson GF. Variation in indications for cataract surgery in the United States, Denmark, Canada, and Spain: Results from the International Cataract Surgery Outcomes Study. Br J Ophthalmol 1998a;82:1107–1111.

Norregaard JC, Bernth-Petersen P, Andersen TF. Changing threshold for cataract surgery in Denmark between 1980 and 1992. Results from the Danish Cataract Surgery Outcomes Study. II. Acta Ophthalmol Scand. 1996;74:604–608.

Norregaard JC, Petersen PB, Andersen TF. Indikationer for kataraktkirurgi i Danmark i 1980 og 1992. Resultater fra the Danish Cataract Surgery Outcome Study. Ugeskr Laeger 1998b;160:3924–3928.

Obstbaum SA. Indications and timing of cataract surgery (editorial). J Cataract Refract Surg 1995;21:483.

Oliver JE, Thulasiraj RD, Rahmathullah R, Baburajan, Katz J, Tielsch JM, Schein OD. Vision-specific function and quality of life after cataract extraction in south India. J Cataract Refract Surg 1998;24: 222–229.

Pager CK, McCluskey PJ, Retsas C. Cataract surgery in Australia: a profile of patient-centred outcomes. Clin Experiment Ophthalmol 2004;32:388–392.

Pesudovs K, Weisinger HS. A comparison of autorefractor performance. Optometry & Vision Science 2004;81554–558.

Pesudovs K, Elliott DB. Refractive error changes in cortical, nuclear and posterior subcapsular cataracts. Br J Ophthalmol. 2003;87:964–967.

Prajna NV, Chandrakanth KS, Kim R, Narendran V, Selvakumar S, Rohini G, Manoharan N, Bangdiwala SI, Ellwein LB. The Madurai Intraocular Lens Study.II: Clinical outcomes. Am J Ophthalmol 1998;125:14–25.

Punnonen H. Sairaaloiden ja sairaanhoitopiirien tammi- joulukuu 2005. Suomen Kuntaliitto. esh05 1–12:26.

Raasch TW, Bailey IL, Bullimore MA. Repeatability of visual acuity measurement. Optometry Vis Sci 1998;75:342–348.

Richter-Mueksch S, Zehetmayer M, Radner W, Kaider A, Velikay.Parel M. Influence of sex, visual acuity, and systemic disease on delayed presentation for cataract surgery in Austria. J Cat & Refr Surg 2001;27:1999–2001.

Rosenfield M, Chiu NN. Repeatability of subjective and objective refraction. Optom Vis Sci 1995;72:577–579.

Rosser DA, Laidlaw DA, Murdoch IE. The development of a ”reduced logMAR” visual acuity chart for use in routine clinical practice. Br J Ophthalmol 2001;85:432–436.

Rouhiainen P, Rouhiainen H, Salonen JT. The impact of early lens opacity progression on visual acuity and refraction. Ophthalmologica 1997;211:242–246.

Rubin A & Harris WF. Refractive variation during autorefraction. Multivariate distribution of refractive status. Optom Vis Sci 1995;72:403–410.

Saw SM, Tseng P, Chan WK, Chan TK, Ong SG, Tan D. Visual function and outcomes after cataract surgery in a Singapore population. J Cataract Refract Surg 2002;28:445–453.

Sheedy J, Schanz P, Bullimore M. Evaluation of an automated subjective refractor. Optom Vis Sci 2004;81:334–340.

Shlaer S. The relation between visual acuity and illumination. J Gen Physiol 1937;21:165–188.

Siderov J, Tiu AL. Variability of measurements of visual acuity in a large eye clinic. Acta Ophthalmol Scand 1999;77:673–676.

Sjöstrand JB, B.Bergman B, Z.Popovic Z. Declining visual acuity in healthy eyes with age. Calculation of loss of retinal ganglion cells in the elderly and old. Poster ARVO 2004.

Smith G. Relation between Spherical Refractive Error and Visual Acuity. Optom Vis Sci 1991;68:591–598.

Stakes; National Research and Development Centre for Welfare and Health , Finland. Extract from database; Oct.. 2000.

Stakes; National Research and Development Centre for Welfare and Health, Finland. Report 2005.

Statistical Yearbook of Finland. Report 2001.

Stenevi U, Lundström M , Thorburn W. A National Cataract Register I. Description and epidemiology. Acta Ophthalmol Scand 1995;73:41–44.

Street DA, Javitt JC. National five-year mortality after inpatient cataract extraction. Am J Ophthalmol 1992;113:263–268.

Superstein R, Boyaner D, Overbury O. Functional complaints, spatial contrast sensitivity, and glare disability in preoperative and postoperative cataract patients. J Cataract Refract Surg. 1999;25:575–581.

Tan AG, Wang JJ, Rochtchina E, Jakobsen KB, Mitchell P. Increase in cataract surgery prevalence from 1992–1994 to 1997–2000: analysis of two population cross sections. Clinical & Experimental Opthalmology 2004;32(3):284–288.

Taylor HR, Keeffe JE. World blindness: a 21st century perspective. Br. J Ophthalmol 2001;85:261–266.

Taylor HR. Cataract surgery: how much surgery do we have to do? Br J Ophthalmol 2000;84:1–2.

The Italian-American Cataract Study Group. Incidence and progression of cortical, nuclear, and posterior subcapsular cataracts. Am J Ophthalmol 1994;118:623–631.

Thibos L, Hong X, Bradley A. Applegate RA: Accuracy and precision of objective refraction from wave front aberrations. J Vision. 2004;4:329–351.

Thibos LN, Wheeler W, Horner D. Power vectors: an application of Fourier analysis to the description and statistical analysis of refractive error. Review. Optom Vis Sci 1997;74:367–375.

Uusitalo RJ, Brans T, Pessi T, Tarkkanen A. Evaluating cataract surgery gains by assessing patients'quality of life using the VF-7. J Cataract Refract Surg 1999;25:989–994.
Van den Brom HJ, Kooijman AC, Blanksma JL, van Rij G. Measurement of visual acuity with two different charts; a comparison of results and repeatability in patients with cataract. Docum Ophthalmol 1995;90:61–66.
Vanden Bosch ME, Wall M. Visual acuity scored by the letter-by-letter or probit methods has lower retest variability than the line assignment method. Eye 1997;11:411–417.
Westheimer G, Liang J. Influence of light scatter on the eye's optical performance, J Opt Soc Am Ac 1995;12:1417.
Westheimer G. Visual Acuity. In: Adler's Physiology of the Eye. Mosby, St. Louis, Missouri 2003;453–469.
Westheimer G. Scaling of visual acuity measurements. Arch Ophthalmol 1979;97:327–330.
WHO Study Group on the Prevention of Blindness, Geneva, 6–10 November 1972.
Zadnik C, Mutti DO, Adams AA. The repeatability of measurement of the ocular components. Invest Ophthalmol Vis Sci 1992;33:2325–2333.

Appendices 1–3

Appendix 1. Conversion between Snellen and logMAR values.

Any Snellen value ($V_{Snellen}$) can be converted to logMAR by calculating minus $\log10(V_{Snellen})$ = logMAR. Likewise, logMAR can be converted back to Snellen values by calculating $V_{Snellen} = 10^{-\,logMAR}$.

Imaginary patient group to demonstrate VA change calculations

	Snellen VA_1	Snellen VA_2	logMAR VA_1	logMAR VA_2	Change, logMAR, $VA_2 - VA_1$*)	Change, log lines, $VA_2 - VA_1$*
Pat 1	0.1	0.3	1.00	0.52	0.48	4.8
Pat 2	0.8	1	0.10	0.00	0.10	1.0
Pat 3	0.7	1.2	0.15	–0.08	0.23	2.3
Pat 4	0.3	0.5	0.52	0.30	0.22	2.2
Mean			**0.44**	**0.19**	**0.26**	**2.6**
Standard deviation			0.42	0.28		
Standard deviation of mean			0.21	0.14		
Average Snellen**	0.38	0.53				

* Converted to + sign to show improvement
** Average Snellen values are obtained by changing mean logMAR to Snellen values

Direct calculation of the mean of Snellen values would give erroneous mean values of 0.48 (VA_1) and 0.75 (VA_2), respectively.

Appendix 2. Calculation of the mean of refractive values

Transformation from standard notation values to vector values is done according to Harris (1990a) (Section 2.4.2: Table 1). The results of the calculation of the mean of refractive values RV1, RV2 and RV3 and the difference of RV1 and RV2 are shown in Appendix 2.

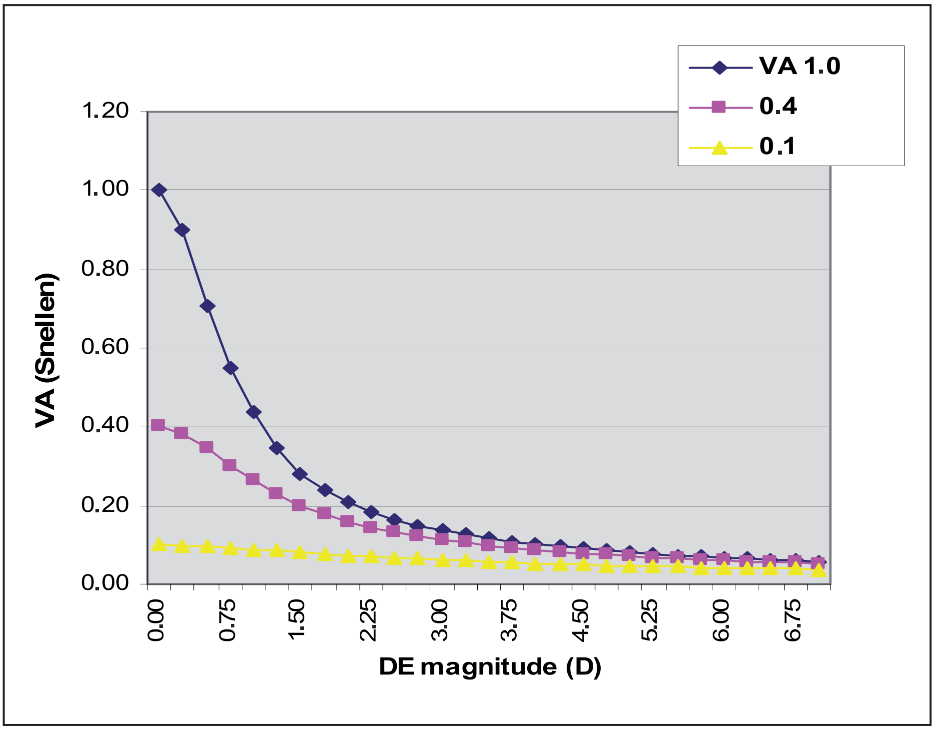
Example of three refractive values, RV $_{1\text{-}3}$ (imaginary values), conversion to vector forms, average and difference of refractions 1 and 2 (vector form, conventional spherocylindric form)

	RV, conventional			RV, vector values (D)			Reversion to conventional spherocylinder		
	Fs(D)	Cyl(D)	ax(deg)	f11	f12	f22	Fs(D)	Cyl(D)	ax(deg)
RV_1	+1	+3	20	1.35	−0.96	+3.65			
RV_2	−2	+2.5	40	−0.97	−1.23	−0.53			
RV_3	+2	0		+2.00	0	+2.00			
Average of $RV_{1,2,3}$				+0.79	−0.73	+1.71	+0.39	+1.72	29.1
Difference of RV_2 and RV_1 (2–1)				−2.32	−0.27	−4.18	−2.28	−1.94	172

The difference of RV_2 and RV_1 can be interpreted as giving the value of the lens that should placed on RV_1 to get RV_2 ; e.g. change in refractive state after surgery or difference between two measurements of refractive power.

Appendix 3a and 3b. Dependence of visual acuity change on defocus magnitude in different VA classes

An estimate of VA change because of incorrect refractive correction can be estimated by a formula based on empirical values of defocus (Section 2.6.8: Table 2). Using this formula, $1/VA = 1/(1/VA_{BC} + 1/VA_{DE} - 1)$ (Methods section 4.4), where VA is visual acuity with defocus (Snellen decimal), VA_{BC} visual acuity with best correction and VA_{DE} is visual acuity of the normal eye with defocus DE, estimates of defocus on VA in different visual acuity groups can be calculated (Appendix 3a and 3b).



Appendix 3a. Visual acuity dependence on BCVA and defocus magnitude

Appendix 3b. Estimate of refractive error effect on VA in different VA classes

BCVA, Snellen (logMAR)	Refractive error (sf/cyl/ax)	DE	VA, Snellen (logMAR) with refractive error of DE 0.75D	Decrease of VA, logMAR (BCA-VA with DE 0.75D and 4.0D)
1.6; (–0.20)	–0.5/1.25/20	0.75D	0.7; (0.16)	0.36
0.4; (0.40)	–0.5/1.25/20	0.75D	0.3; (0.52)	0.12
0.05; (1.30)	–0.5/1.25/20	0.75D	0.05; (1.32)	0.02
0.05; (1.30)	–4.0/6.0/20	4.0D	0.03; (1.46)	0.16

A refractive error of sf –0.5 cyl 1.25 ax 20° decreases VA from 1.6 to 0.7 (decrease of 0.36 logMAR units) or from 0.4 to 0.3 (decrease 0.12 logMAR), but there is practically no decrease in VA 0.05 (0.02 logMAR). A refractive error of sf –4.0 cyl 6.0 ax 20 (DE 4.0D) decreases VA from 0.05 to 0.03 (0.16 logMAR).